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TECHNICAL REPORT NO. 534-45

CAVITATION TUNNELS IN FOREIGN MODEL BASINS
AND RESEARCH INSTITUTIONS.

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TECHNICAL REPORT NO. 534-45.

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CAVITATION TUNNELS IN FOREIGN MODEL BASIN
AND RESEARCH INSTITUTIONS.

SUMMARY

In 1930 a closed jet cavitation tunnel for testing model propellers was constructed at the Hamburgische Schiffbau Versuchsanstalt. In subsequent years alterations were accomplished to avoid cavitation in the elbow downstream from the test section, to eliminate the thrust correction due to the pressure differences inside and outside the tunnel, and to minimize the frictional torque measured by the dynamometer. In recent years, Dr. Lerbs conducted basic research tests to determine which variables have an important influence on model propeller cavitation tests. It was concluded that the model Reynolds number should be greater than 0.8×10^5 and the Froude number should lie between certain minimum and maximum limits determined from the H.S.V.A.¹ basic tests. Preliminary tests of a single propeller indicated no effect on performance when varying the air content of the tunnel water.

A new large cavitation tunnel with test section 47.24 inches high by 94.49 inches wide, and with 16 knots water

¹Hamburgische Schiffbau Versuchsanstalt.

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Summary, Cont'd.

speed was constructed at H.S.V., between 1940 and 1943. Complete ship models or torpedo stern sections can be mounted in the tunnel for conducting cavitation tests with the propellers operating in the wake stream. Bombing damage prevented service operation of the tunnel.

The original Göttingen general research cavitation tunnel built in 1927 was reconstructed as a "free-jet" tunnel in 1942. Research problems such as the determination of constant pressure surfaces for aircraft, the development of underwater rockets, and the study of the air-water entry problem were investigated by means of cavitation tests at cavitation numbers as low as 0.01. The effects of dissolved air in the tunnel water were considered by measuring the cavitation bubble pressure by a simple method and substituting the bubble pressure for the vapor pressure in the determination of the cavitation number.

At Heidenheim a small cavitation tunnel was constructed about 1937 for the purpose of testing Voit-Schneider propellers. For high steering angles where the cavitation test results were inaccurate, the influence of cavitation on performance was calculated by a method of Betz.

H.S.V. designed the closed-jet cavitation tunnels for Russia (1932), Japan (1936), Holland (1939), and the Karlstads firm in Sweden (1942). Late designs favored sharper corners with short multiple guide vanes at all corners except the elbow downstream from the test section. This elbow is constructed with a large radius to avoid cavitation.

A new cavitation tunnel for testing hydrofoils in cascade for the purpose of obtaining basic propeller design data was proposed for construction at H.S.V. in late 1941. Lack of materials and war difficulties prevented the construction.

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Summary, Cont'd.

It is recommended that further basic tests be conducted for determining the effects of air content of tunnel water and of sea water on propeller performance under cavitation conditions. The bubble pressure-measuring method used at Göttingen is well suited for such an investigation.

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Introduction, Cont'd.

Inasmuch as the stagnation pressure q_0 varies as the square of the velocity, and the vapor pressure p_v is ordinarily small and of the same order of magnitude for both full scale and model, the absolute static pressure p_0 for identical σ values normally must be considerably lower for the model test than for the full scale. Therefore, in order to study the effects of cavitation on the energy relationships or acoustical properties of bodies moving relative to fluids, variable pressure water tunnels have been designed and constructed in various countries of the world during the past twenty years.

When air or other gases are dissolved in a fluid, which is the usual case, the cavitation bubble pressure may be higher than the vapor pressure for the given temperature. The question arises as to whether the cavitation number should be redefined as,

$$\sigma_b = \frac{p_0 - p_b}{q_0}$$

where p_b = the pressure in the cavitation bubble,

σ_b = cavitation number based on bubble pressure.

The purpose of this report is to describe certain foreign cavitation tunnel installations including design features, developments of instrumentation, and the results of some basic tests concerning the effects of dissolved air or gases and the determination of the fundamental physical variables which have the greatest influence on model propeller test results.

Institutions visited and personnel contacted in obtaining the information for this report were:

1. Hamburgische Schiffbau Versuchsanstalt, Hamburg.

Dr. Ing. H. Lerbs
Ing. Schultze
Ing. Hoppe

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Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

split into two separate channels. This alteration was successful in avoiding cavitation in the elbow at all speeds and further allowed the propeller shaft to be shortened, thereby raising the critical RPM of the dynamometer installation above the operating range.

Originally the model propeller dynamometer was belt-driven by a motor from below, as shown in Fig. 2. The thrust was measured by balancing a beam scale to which the thrust from the drive shaft was transmitted by a thrust bearing and knife edges. The torque was determined by measuring the twist of a calibrated shaft by means of an optical oscilloscope. In an attempt to make the frictional torque of the driving arrangement small and constant, the stuffing gland was driven by an auxiliary shaft from the main dynamometer driving motor at a speed 5 percent less than the propeller shaft speed. The relative speed of 5 percent of the absolute peripheral speed was necessary in order to retain sufficient sensitivity of the thrust measurement. However, because of variations of the pressure of the viscous grease used for sealing the joints, the frictional torque could not be held constant over a period of time and frequent gland repairs were necessary.

After several unsuccessful tests using water sealing of the stuffing glands, the method shown in Fig. 3 was devised. A hollow shaft is driven by the dynamometer. The friction at the forward bearing and the packing gland acts only on the hollow shaft which extends to the forward bearing. The propeller shaft is supported inside the hollow shaft by a ball bearing at the forward end and a ground-in bearing at the after end, and is connected to the hollow shaft by means of a calibrated torsion rod. The ground-in bearing serves as a seal to prevent water from entering between the two shafts. The propeller torque

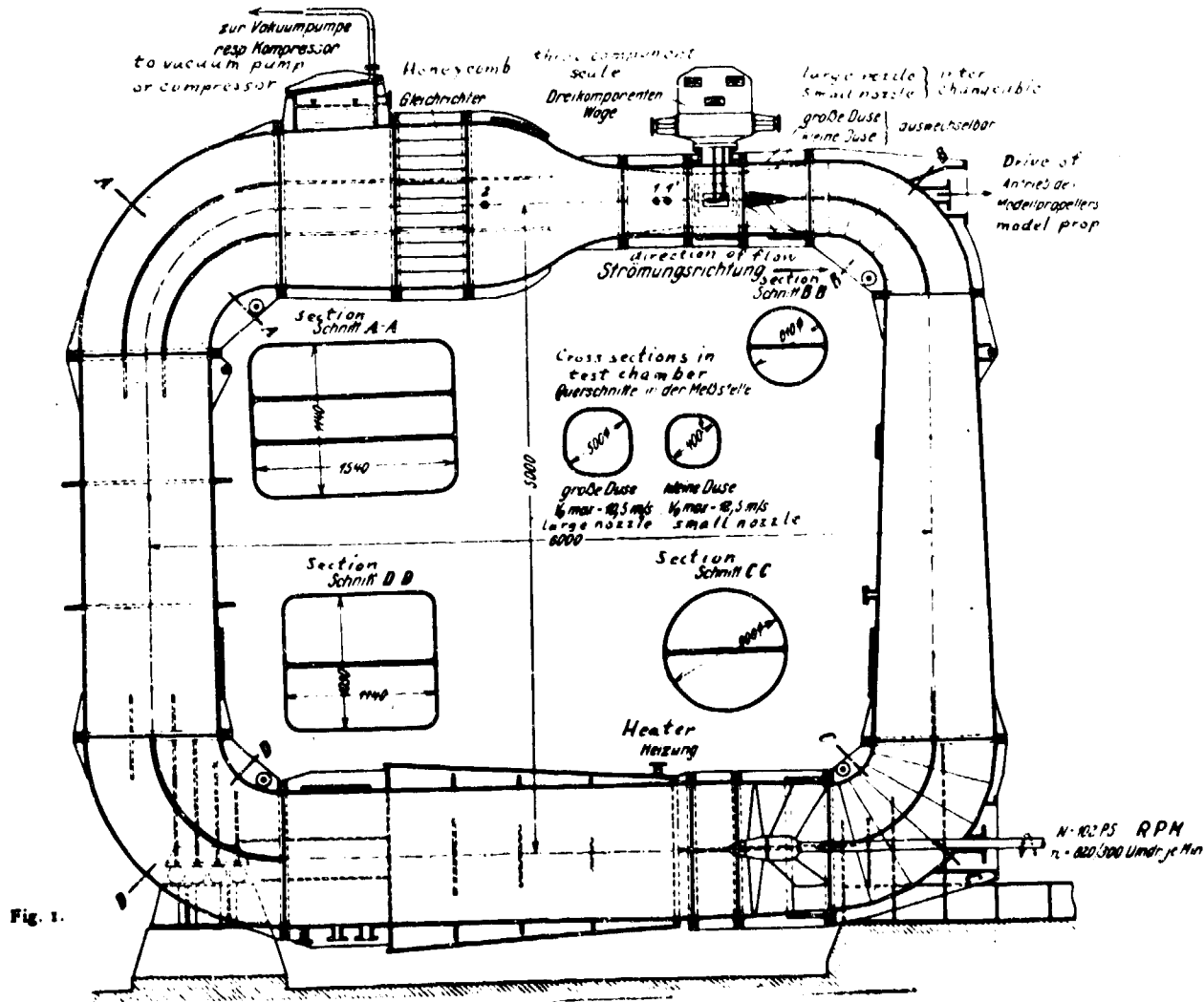


Fig 1

Cavitation Tunnel I of H.S.V.A. as
Originally Constructed (1930)

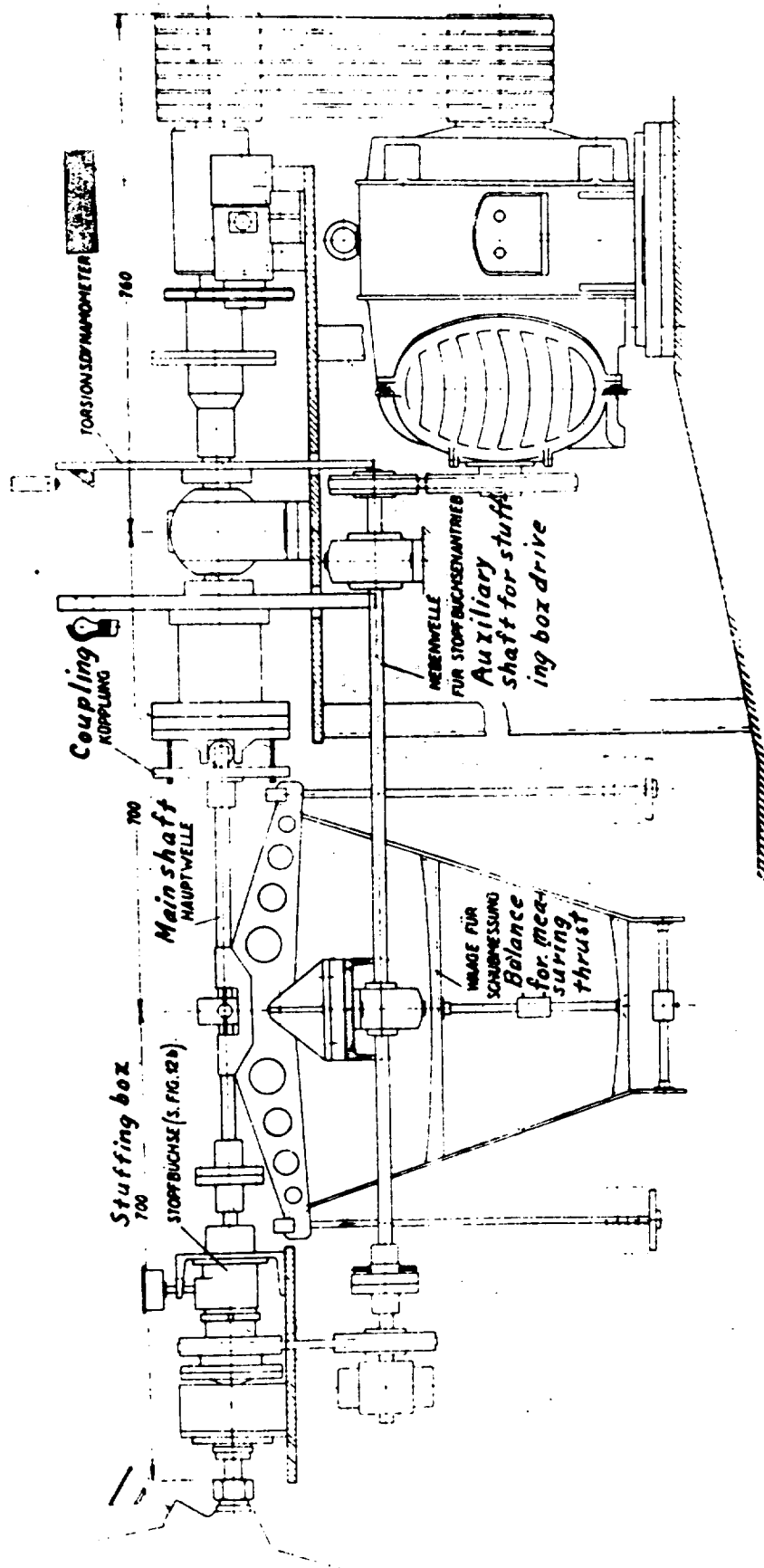


Fig. 2

U.S.V.A. Cavitation Tunnel I Dynamometer
Installation as Originally Constructed (1930)

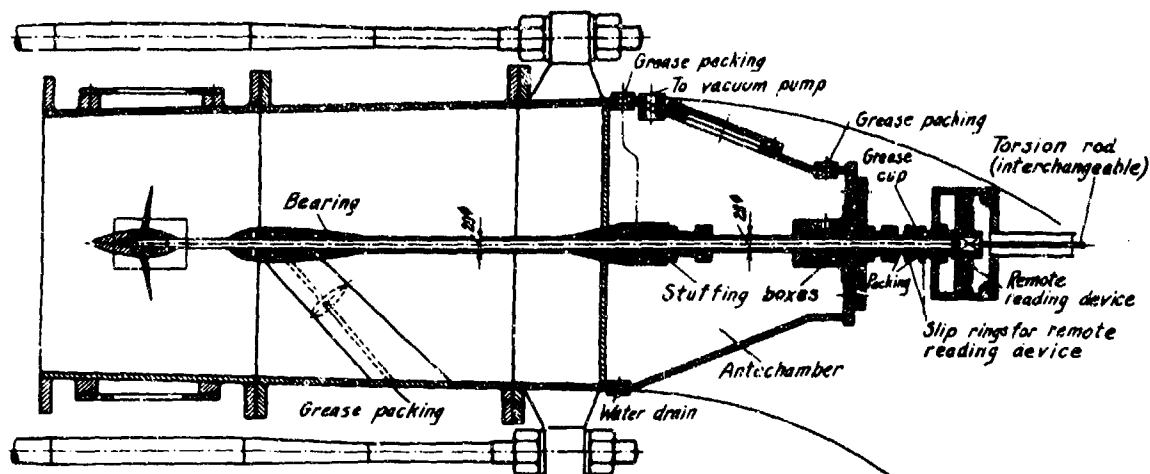


Fig. 3

H.S.V.A. Cavitation Tunnel I Altered Arrangement
of Bearings and Packing Glands on the Propeller Shaft

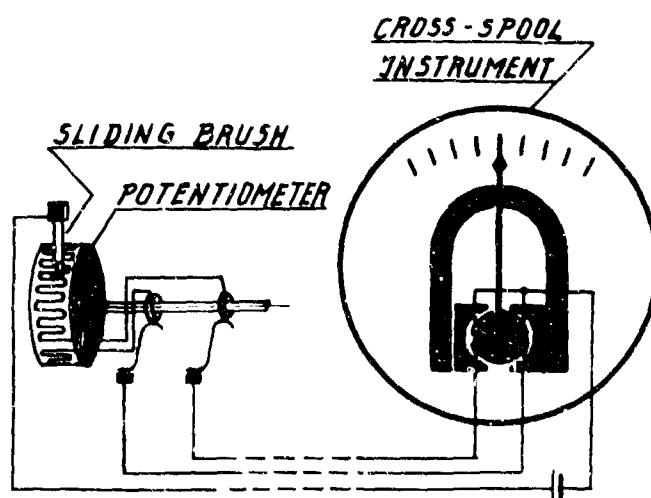


Fig. 4

H.S.V.A. CAVITATION TUNNEL I
SCHEMATIC ARRANGEMENT OF POTENTIOMETER
AND CROSS-SPOOL INSTRUMENT FOR MEASURING TORQUE

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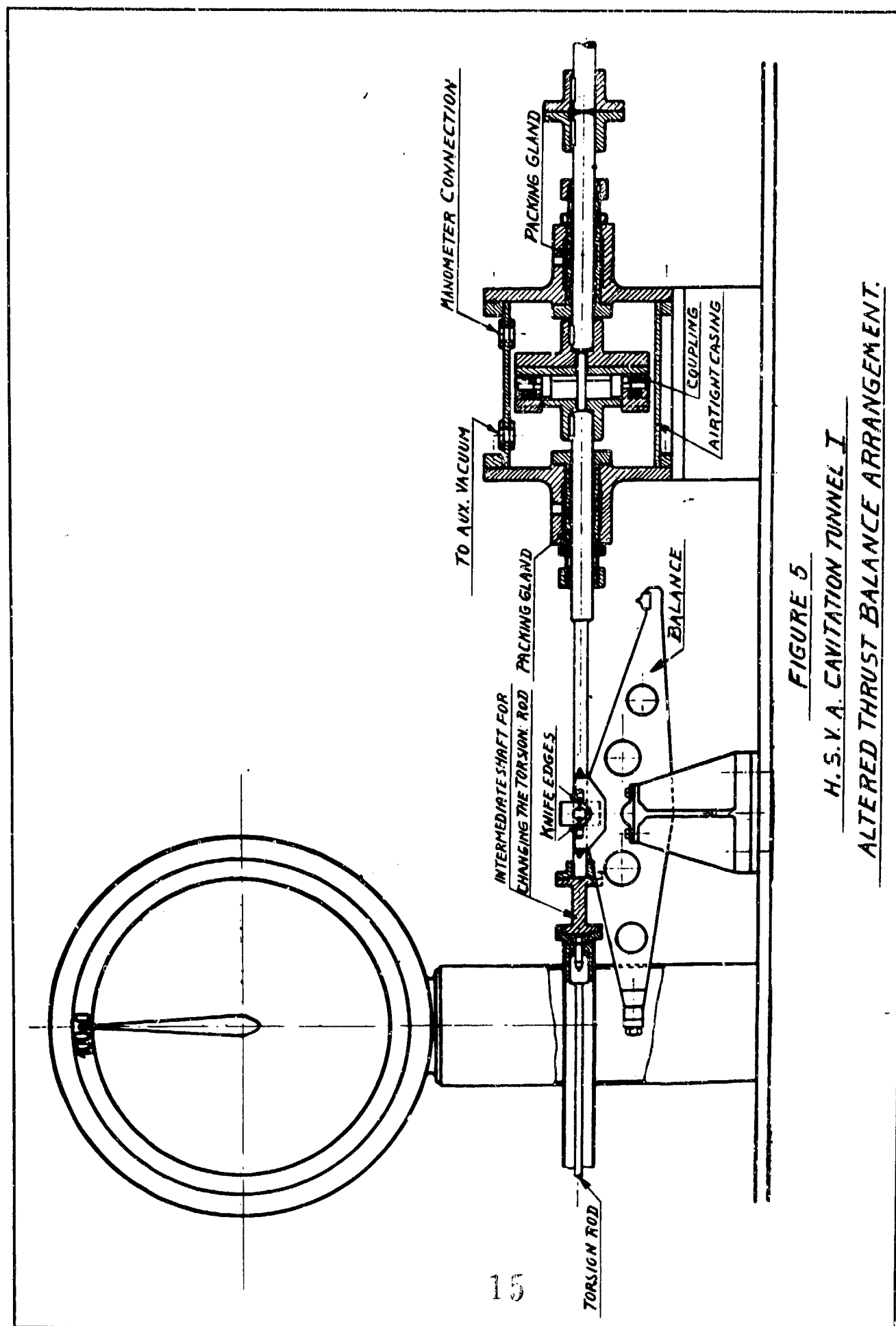
Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

in which the pressure can be regulated by a small vacuum pump and a throttle valve, as shown schematically in Fig. 6. The throttle valve is controlled by a motor in connection with a mercury ring balance. One leg of the mercury ring balance is connected to the test section of the tunnel and the other is connected to the compensating chamber. With a difference in pressure in the two legs, the balance rotates about a knife edge and a relay acts to cut on or off the circuit of the motor which operates the throttle valve. Thus the throttle valve is regulated so that the mercury ring is balanced, and there is equality of pressure in the test section and the compensating chamber. With equal shaft diameters in the tunnel and the compensating chamber, no thrust error due to pressure differences exists.

In practice, the rather complicated mercury ring balance control device frequently failed and maintenance delays overbalanced the value of the automatic control. In the last days of operation of the tunnel the automatic control was removed and a simple mercury manometer, connected between the test section and the compensating chamber, was used as an indicator for manually maintaining equality of the pressure.

For measuring the propeller revolutions, originally a mechanical tachometer with a mechanical stop watch was employed. In 1943 an electrical tachometer with synchronous motor control, manufactured by Irion and Vossler, Schwenningen, was substituted for the mechanical tachometer.

The water speed in the test section is measured by means of a pitot tube in the plane of the model propeller. The pitot tube was calibrated in the towing basin and corrections were made for local non-uniformity of flow, relation of tube cross-section to measuring section, wall effect, and the pressure gradient in the tunnel (1).



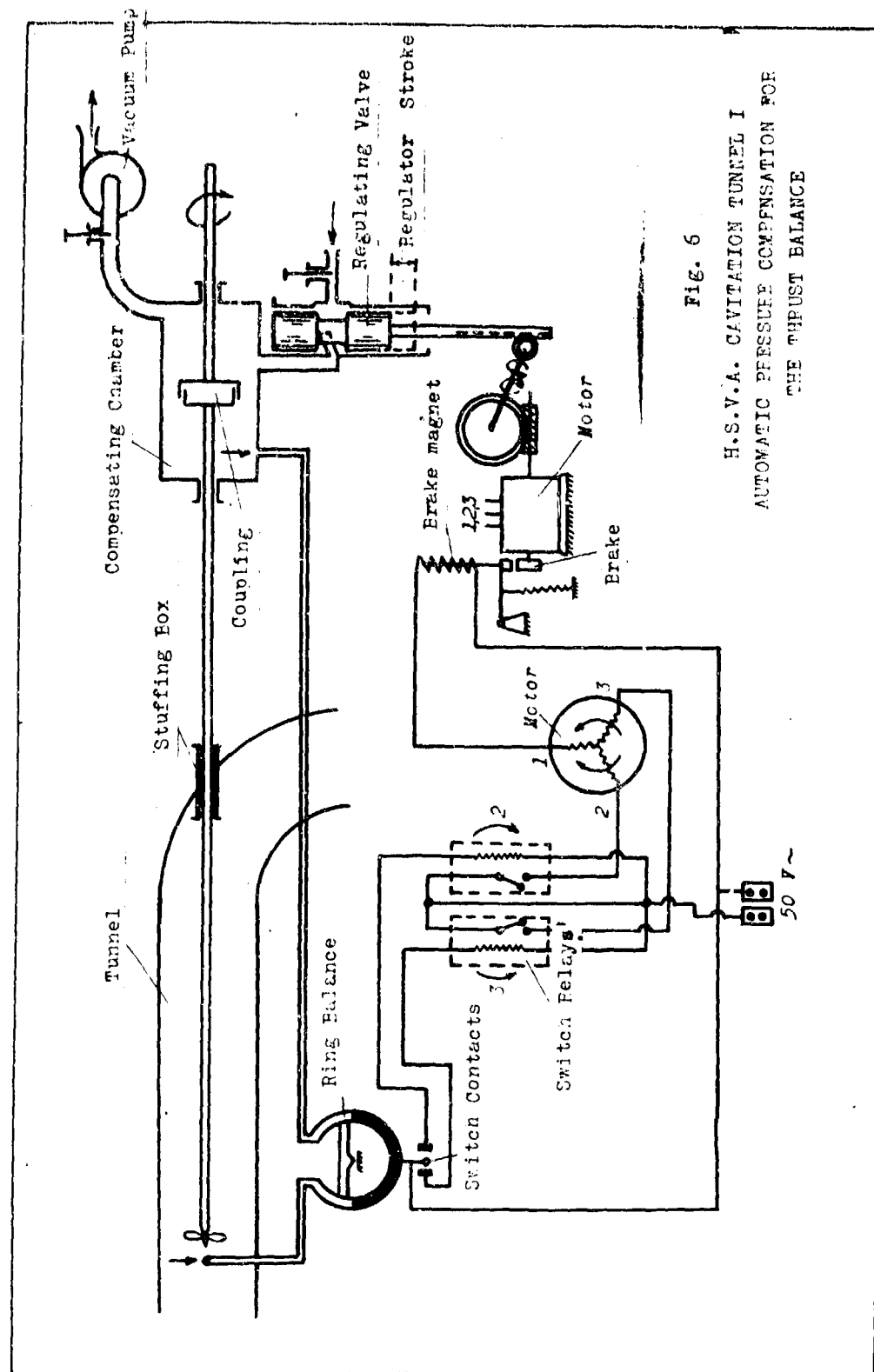


Fig. 6

H.S.V.A. CAVITATION TUNNEL I
AUTOMATIC PRESSURE COMPENSATION FOR
THE THRUST BALANCE

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Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

The static pressure at the center of the propeller model is measured by a mercury manometer as the difference in pressures between the atmosphere and an aperture in the tunnel wall at the height of the shaft center. To regulate the pressure, the vacuum pump is run slowly and a throttle valve in the connecting pipe line is regulated for rough control. Fine control of the pressure is accomplished by a pinch-cock which admits atmospheric air into the water line through a rubber tube. The vacuum pump is reversible for use as a compressor in order to produce pressures slightly above atmospheric.

The original tunnel design contemplated the use of a smaller square nozzle with rounded corners for use in testing thin hydrofoils with a three-component dynamometer. This arrangement was abandoned after a few tests since the dynamometer was not satisfactory and the results did not compare well with wind tunnel data. Dr. Lerbs stated that in testing thin hydrofoils, the length must be kept short to prevent deformation and resultant inaccuracies in the measurements.

On the lower leg of the tunnel is a heating jacket capable of raising the temperature of the tunnel water for removing air bubbles and for controlling the Reynolds number for basic research tests. The heating water in the jacket is supplied by a separate boiler. Only on about five occasions had tests been conducted at elevated temperatures up to about 120° Fahrenheit. At these temperatures, difficulties were encountered with the grease sealing methods. The sealing grease had a tendency to mix with the water and contaminate it. Dr. Lerbs ultimately intended to change the sealing methods and substitute Buna rubber seals for the grease seals.

When the tunnel was originally constructed, the inside surfaces were painted with red lead. Contamination of the water resulted and an additional coat of ordinary grey ship paint was added. This paint peeled and proved unsatisfactory and finally the interior

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Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

$$T = C_1 \rho n^2 d^4$$

$$Q = C_2 \rho n^2 d^5$$

where T = thrust

Q = torque

C_1, C_2 = dimensionless coefficients
for thrust and torque, res-
pectively.

n = revolutions per second.

ρ = mass density of the fluid.

d = diameter

C_1 and C_2 depend on the dimensionless
speed coefficient $k = \frac{v_a}{\pi n d}$

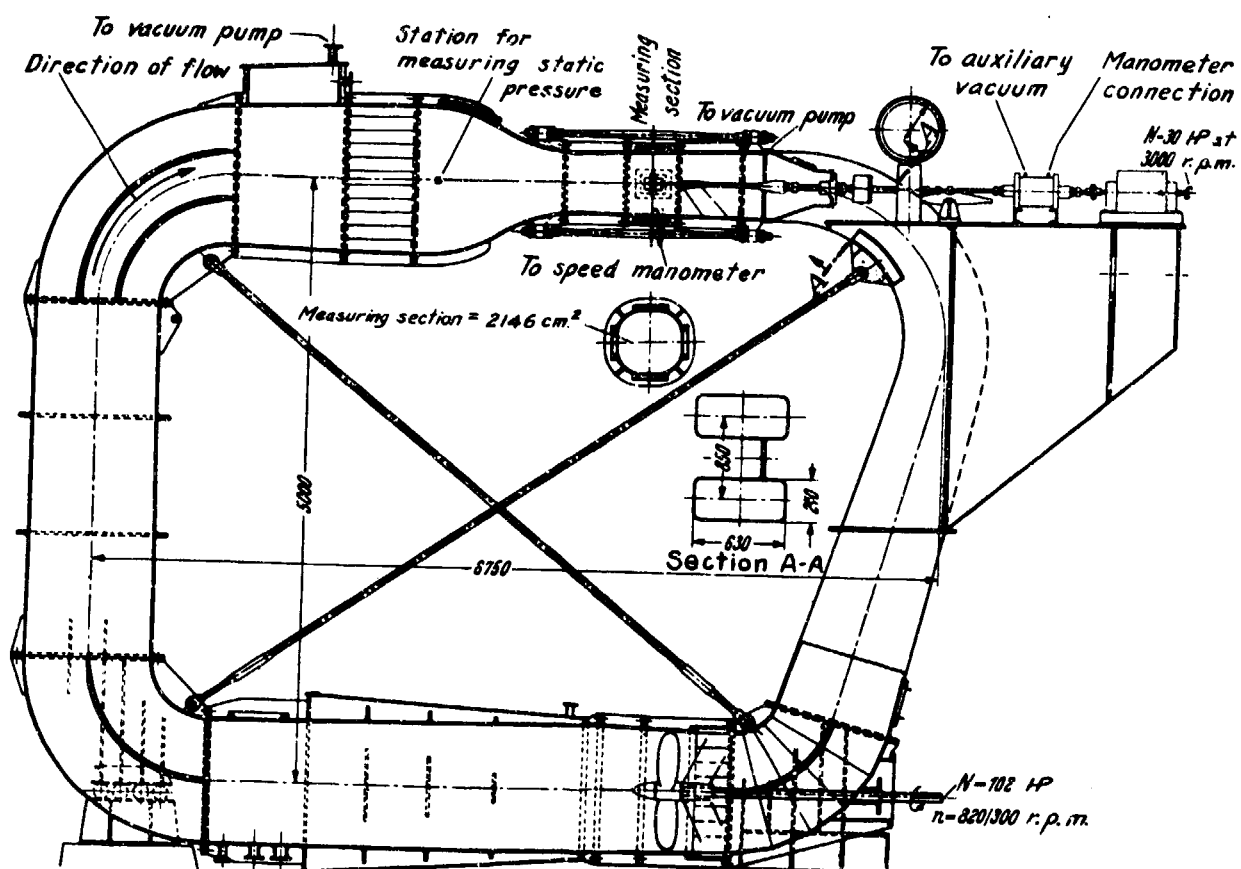


Figure 7
H.S.V.A. Cavitation Tunnel I
Final Altered Arrangement

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Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

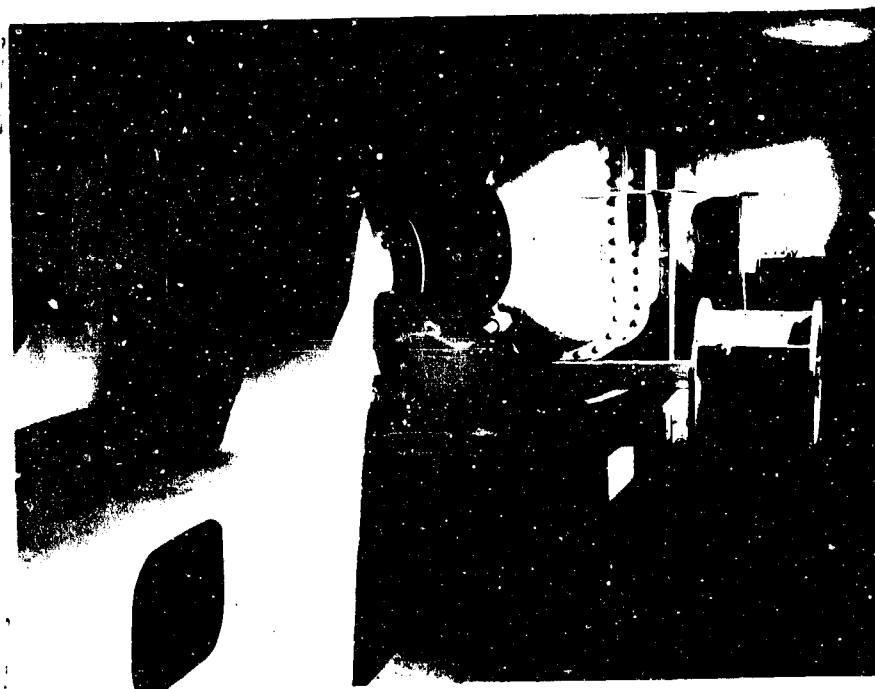


Fig. 8

UPPER SECTION OF H.S.V.A. CAVITATION TUNNEL I, JUNE 1945.

The dynamometer has not been replaced since it was damaged by fire in August 1943. The indentation on the right hand split elbow was caused by an incendiary bomb.

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Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

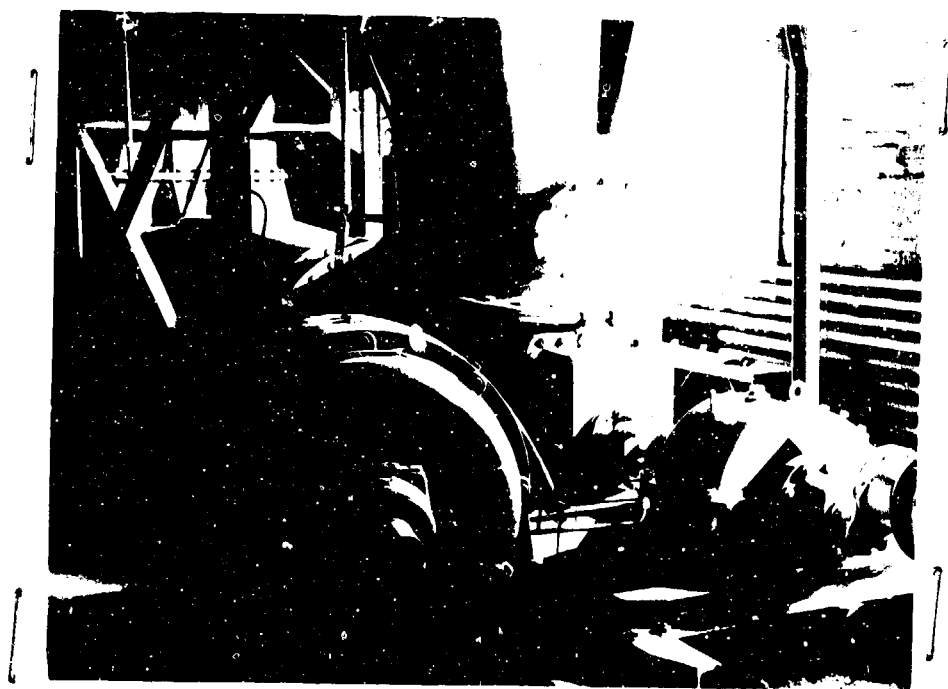


Fig. 9.

LOWER SECTION OF H.S.V.A. CAVITATION TUNNEL I, JUNE 1945.

The repaired driving motor, damaged by fire in August 1943, is not yet reinstalled.

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Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

where v_a = speed of advance.

(b) Consideration of gravity forces leads to the requirement of equality of the Froude number,

$$F = \frac{v_a}{\sqrt{gd}}$$

where g = acceleration of gravity.

(c) Viscosity effects require equality of the Reynolds number,

$$R = \frac{v_a d}{\nu}$$

where ν = $\frac{\mu}{\rho}$ = kinematic viscosity

μ = viscosity

(d) The parameter for the formation of cavities in fluids can be defined as,

$$\frac{p_0 - p'}{q_0}$$

p_0 = absolute static pressure

p' = the critical pressure for cavity formation

q_0 = stagnation pressure

For gas-free fluids, the vapor pressure p_v is the critical pressure, or

$$\sigma = \frac{p_0 - p_v}{q_0} = \text{the cavitation number.}$$

The cavitation parameter σ and the Froude number F are related, in that for equal local cavitation numbers at all corresponding blade elements of the

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Cavitation Tunnel I of Hamburgische Schiffbau Versuchsanstalt, Con't.

To summarize these basic requirements,

$$T = \rho n^2 d^4 C_1 (\lambda, F, \bar{R}, \frac{p_o - p'_w}{q_o}, T.F.,)$$

$$Q = \rho n^2 d^5 C_2 (\lambda, F, \bar{R}, \frac{p_o - p'_w}{q_o}, W, T.F.)$$

It is impossible to meet the requirements of all of the above basic laws in model testing. For example,

$$F = \text{constant}, v_{am} = v_{as} / \lambda_m$$

$$\bar{R} = \text{constant}, v_{am} = v_{as} \lambda_m^{1/2}$$

$$W = \text{constant}, v_{am} = v_{as} \sqrt{K_2/K_1}$$

$$T.F. = \text{constant}, v_{am} = v_{as} / \lambda_m$$

where v_{as} = full scale speed of advance

v_{am} = model speed of advance

λ_m = ratio of full scale to model

The Froude and time laws require a lower speed of advance for the model than the full scale while the Reynolds and Weber laws require a much greater speed of advance for the model than for full scale. Lerbs ran a series of basic tests in order to determine which variables have the greater influence on the thrust and torque coefficients.

2. Air Content Studies.

In 1937 and 1938 Numachi and Kurokawa in Tokyo reported on tests carried out with small glass nozzles to determine the dependence of the pressure at which gases precipitate from water

Abb. 7

TESTS OF NUMACHI AND KUROKAWA

NOZZLE 22

DIAMETER OF SMALLEST CROSS SECTION 1.098mm.

LENGTH OF SMALLEST CROSS SECTION 2.80mm.

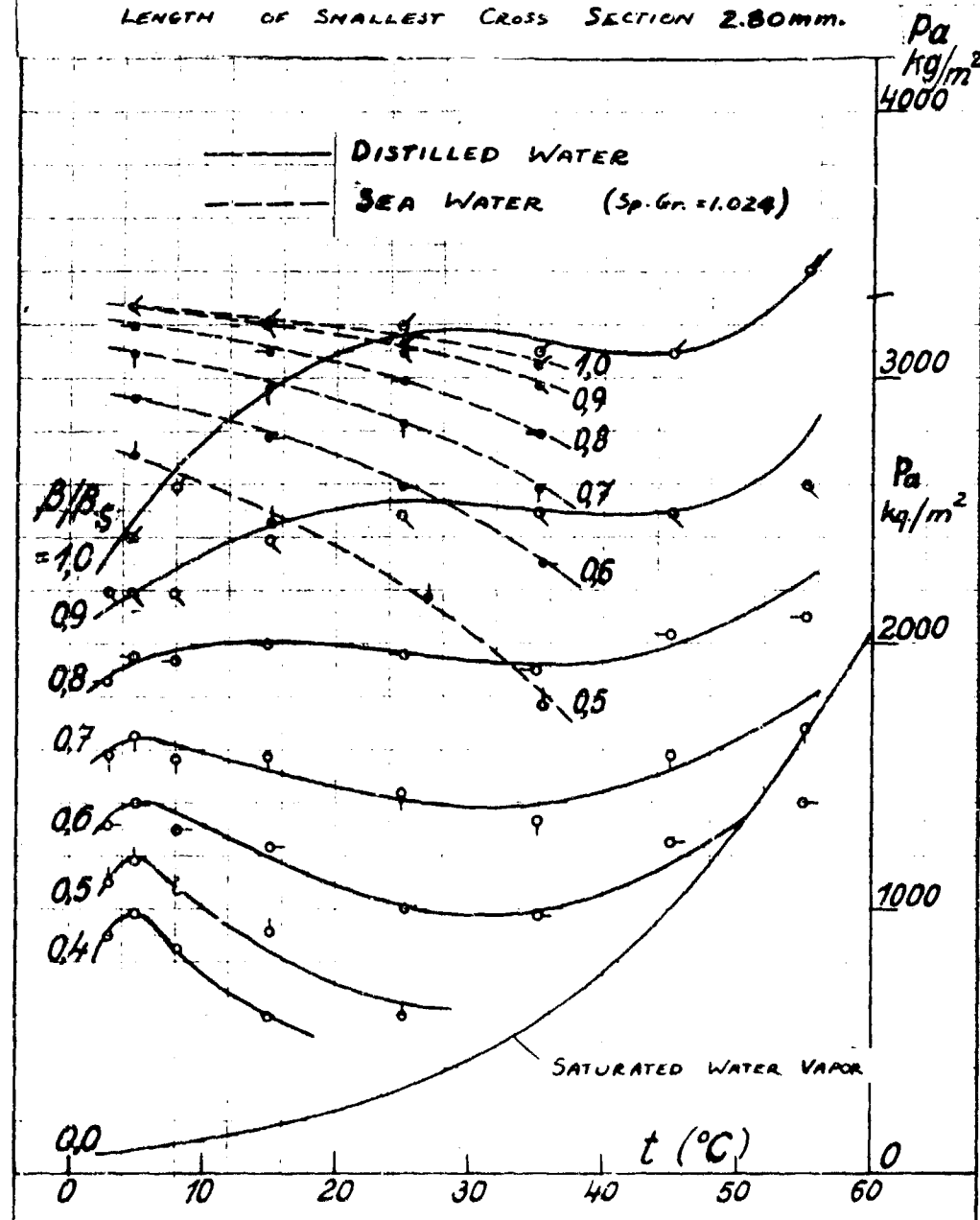


FIGURE 10

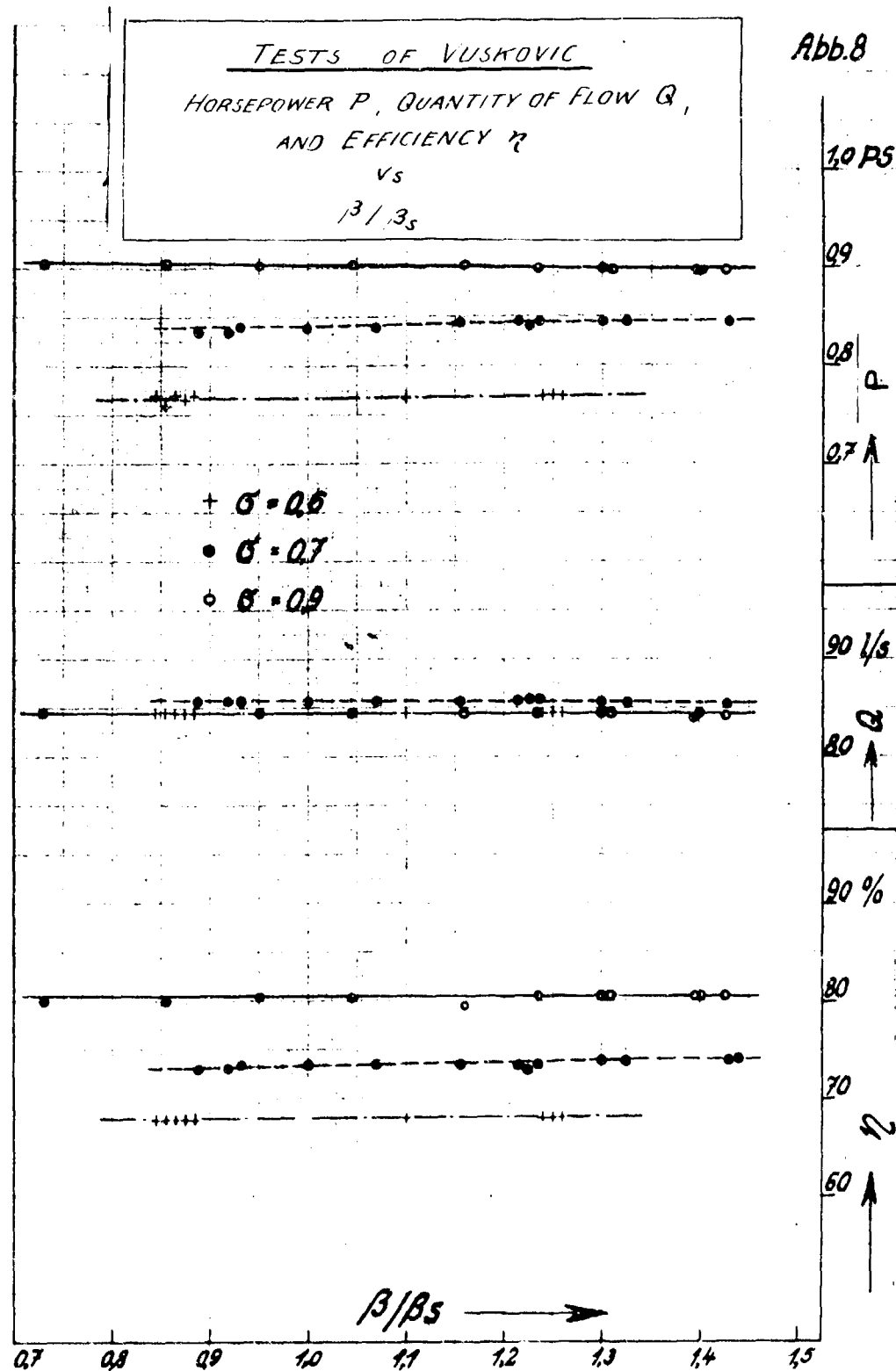


FIGURE 11

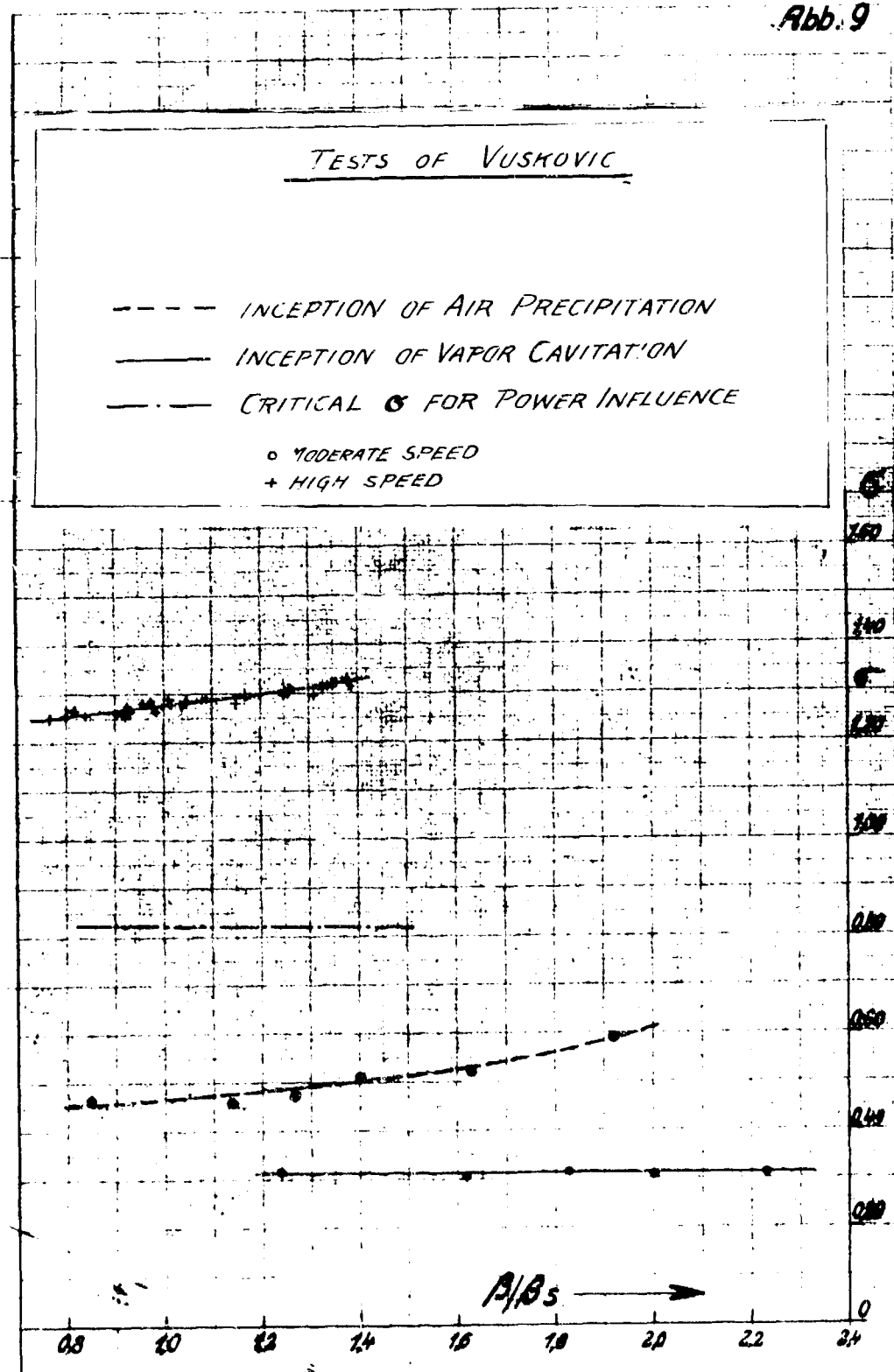


FIGURE 12

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Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

From stroboscopic inspection, Vuskovic noted that air precipitation and vapor cavitation differed appreciably in appearance in that air precipitation appeared as a dim microscopic foam on the surface and vapor cavities appeared as large clear bubbles in the foam. From visual observation of these phenomena, plots of the cavitation numbers associated with the beginning of air precipitation and vapor cavitation are also shown in Fig. 12. The inception of air precipitation occurred at higher cavitation numbers with increasing air content³, but inception of vapor cavitation was independent of air content at the lower rotor speeds, and was only slightly dependent at high rotor speeds.

While the work of Vuskovic indicated that performance of turbines with varying degrees of cavitation was independent of air content, the values of air content of water used in his tests were not nearly low enough to cover the range which is normally encountered in closed circuit cavitation tunnels. Therefore Lerbs constructed the apparatus shown in Fig. 12 for measuring the precipitation pressure of the tunnel water. He desired to determine the dependence of the propeller forces on the precipitation number, σ_{pr} , with a constant cavitation number, σ_c , where the precipitation number,

$$\sigma_{pr} = \frac{p_0 - p_a}{q_0} \quad \text{and } p_a = \text{air precipitation pressure. While } p_a$$

is dependent on the absolute air content as well as the temperature, the difficult determination of air content was not necessary for these tests since p_a was to be calculated directly.

The measuring apparatus, Fig. 13, consisted of a glass nozzle, a submersed centrifugal pump, and a throttle valve connected in parallel with the tunnel test section. By these means the speed of flow and pressure in the nozzle could be set independently of the conditions in the tunnel. The centrifugal pump, located at a low level, was submersed in water.

³Vuskovic calculated the absolute air content from the conventional Winkler chemical test for oxygen content.

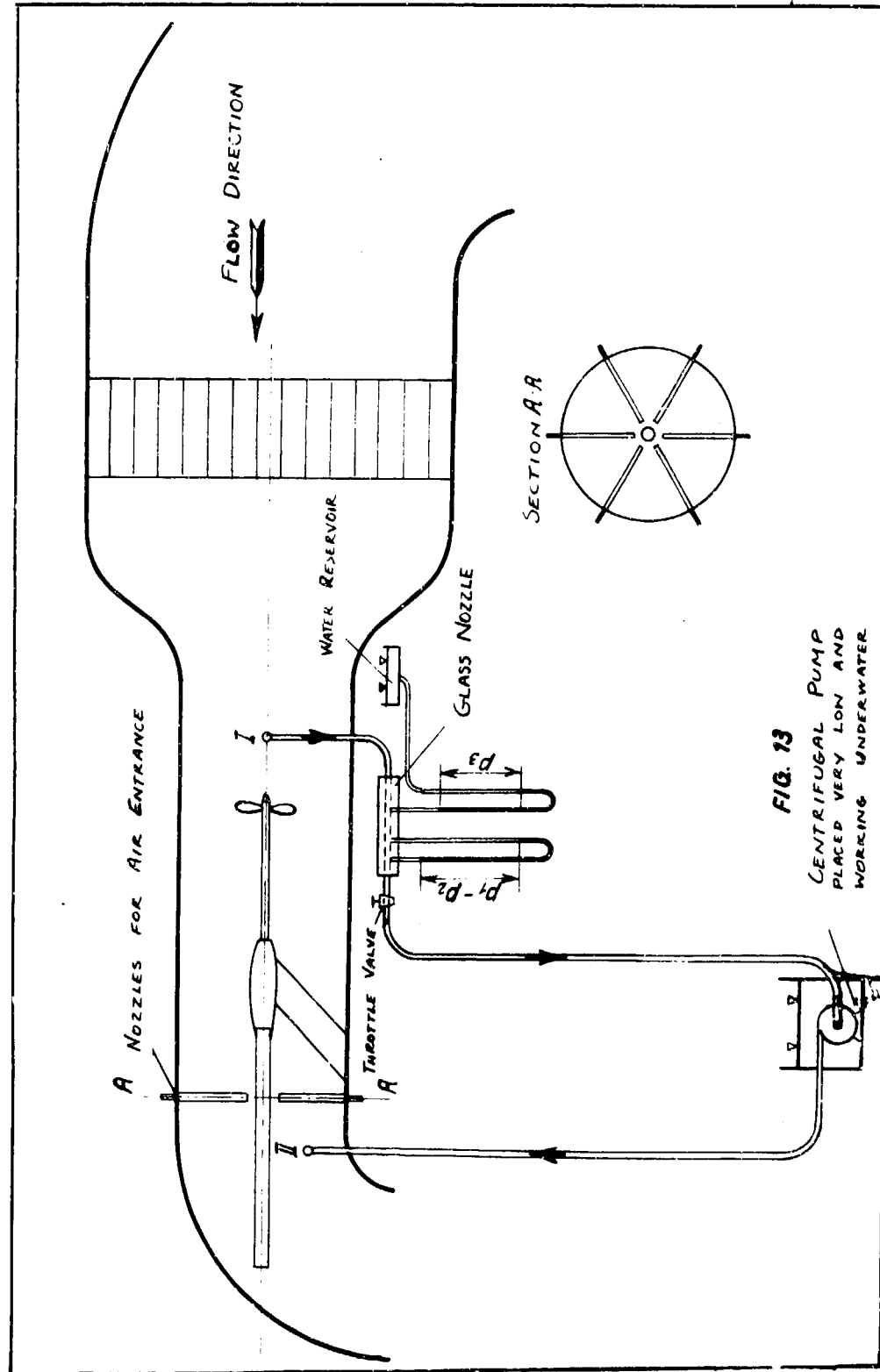


FIG. 13
CENTRIFUGAL PUMP
PLACED VERY LOW AND
WORKING UNDERWATER

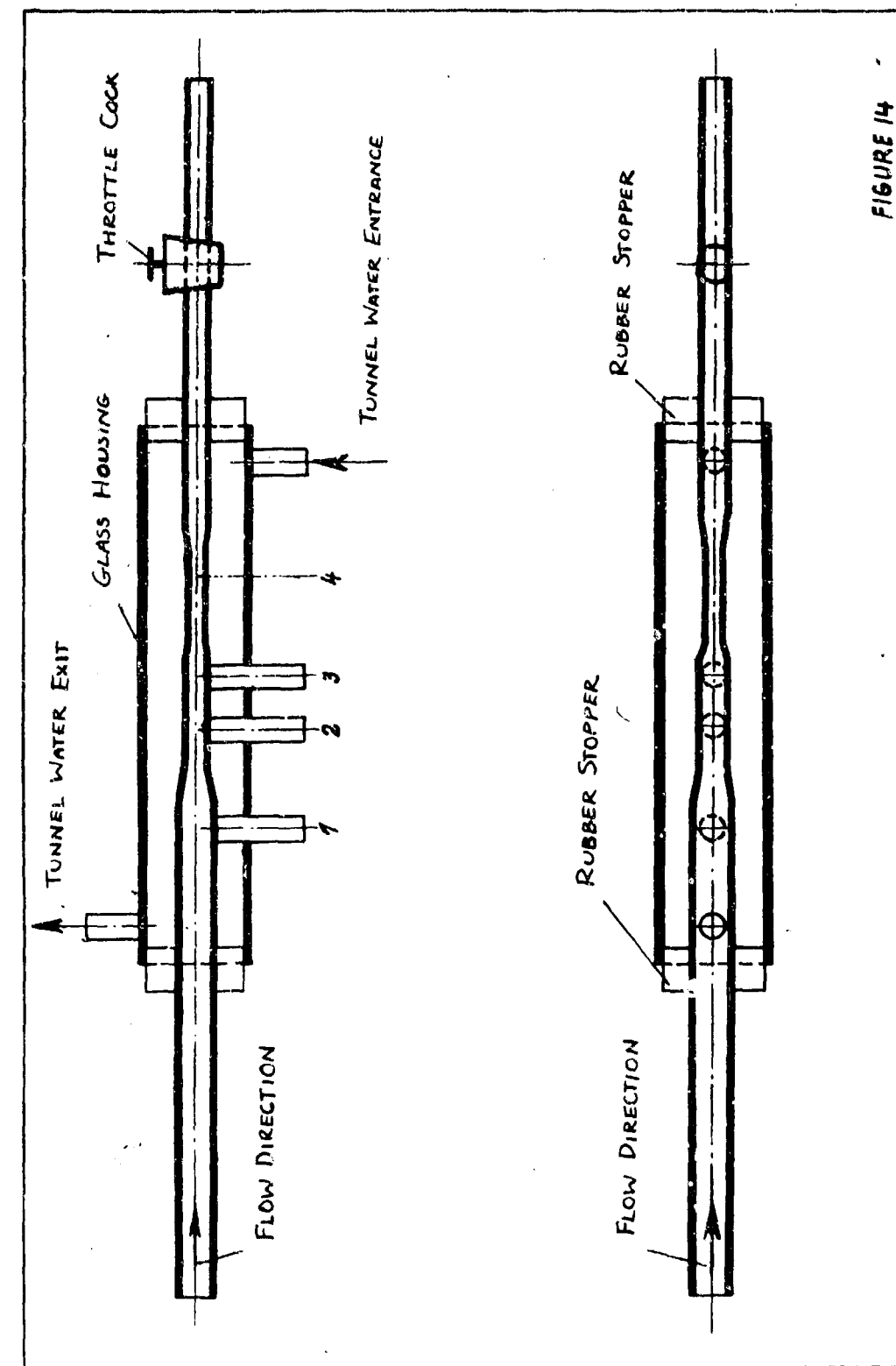


FIGURE 14

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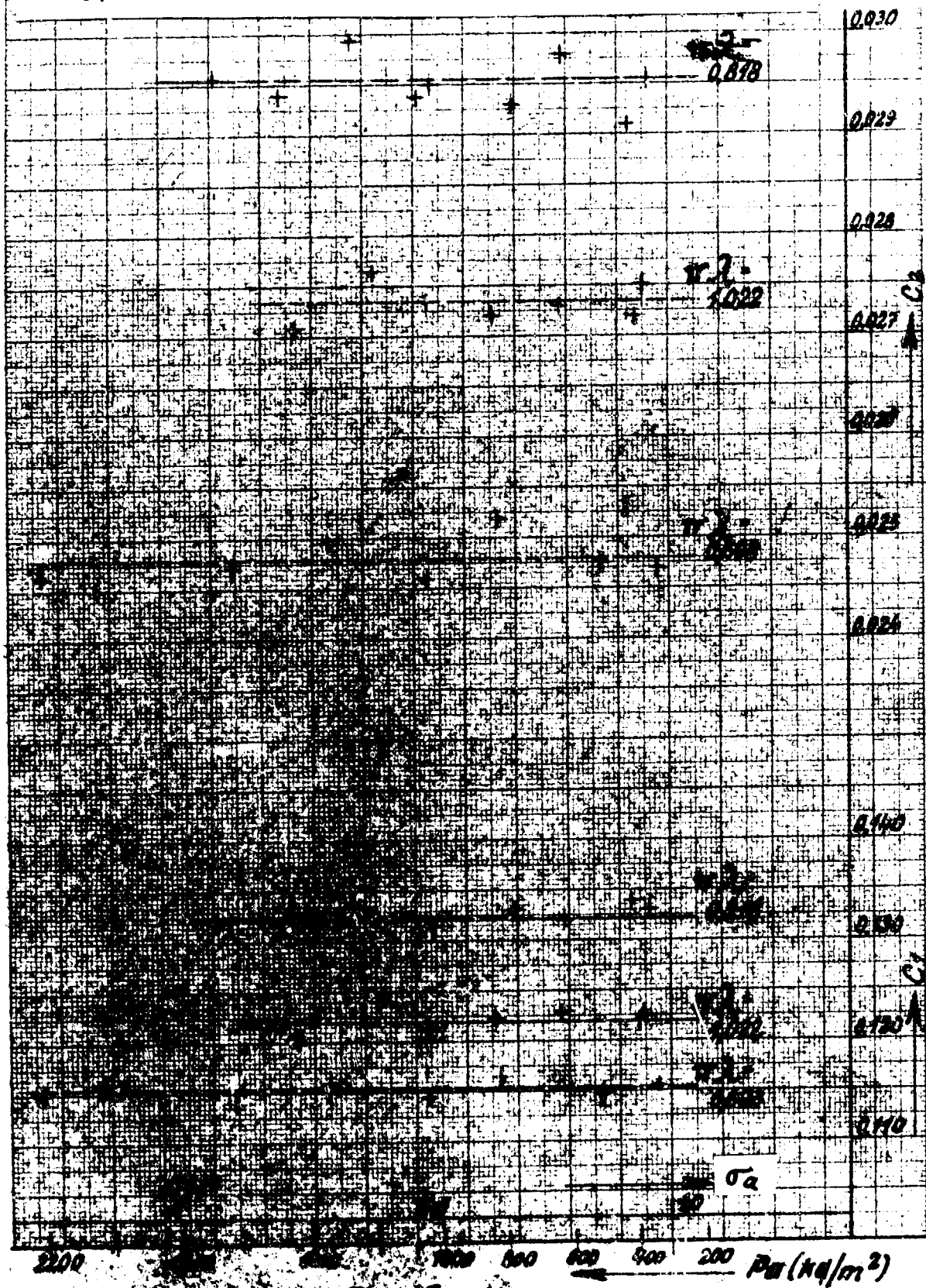
Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

The precipitation pressure could be determined approximately by adjusting the speed through the nozzle so that clouding in the nozzle was observed to begin or cease. It was also determined that the clouding due to air precipitation was associated with a sharp rustling noise⁴. Therefore, a sound pickup was mounted on the nozzle and was used as a more accurate indicator. The precipitation pressure was determined for the point at which the crackling sound ceased. The acoustical and visual methods did not give exactly the same results, for the noise persisted slightly after clouding disappeared when decreasing the velocity of flow through the glass nozzle.

The scope of Lerbs air content studies included testing the model of only one propeller design of the Schaffran B₂ series with 3 blades, circular back sections, pitch ratio 1.2, and expanded area ratio 0.56. The precipitation pressure p_p and the precipitation number p_a were varied, while holding the speed ratio and the cavitation number constant, and thrust and torque were measured. Figures 15 and 16, representing tests at $\sigma = 1.10$ and 0.70 respectively, show no systematic variation of the thrust and torque coefficients for constant speed ratios when varying the precipitation pressure. Fig. 17 indicates the dependence of the speed coefficient on the precipitation pressure for the beginning of precipitation at the blade leading edge with constant cavitation numbers. The results show some scattering, but no systematic dependence of the propeller forces on air content are present, even at the lower air content values in which the precipitation pressure approaches the vapor pressure.

⁴The realization that air precipitation was associated with a sharp rise in noise level was utilized by Lerbs in the design of noise-free propellers for submarines and torpedoes. The minimum pressure on the suction side of the blades was designed to be greater than the air precipitation pressure for sea water determined from Murchi's data (Fig. 10).

$$\sigma = \frac{p_0 - p_v}{\rho/2 \cdot v_a^2} = \text{const.} = 1.10; v_a = 5.50 \text{ m/s.}; p_0 = 154 \text{ kg/m}^2.$$



C_1 and C_2 VS σ_a : $p_0 - p_a$
 $P/2 - \sigma_a^2$

$\sigma \cdot \frac{p_0 - p_a}{P/2 \cdot \sigma_a^2}$: const. = 0.70; $\sigma_a = 5.50$ m/s; $P_0 = 136$ kg/m²

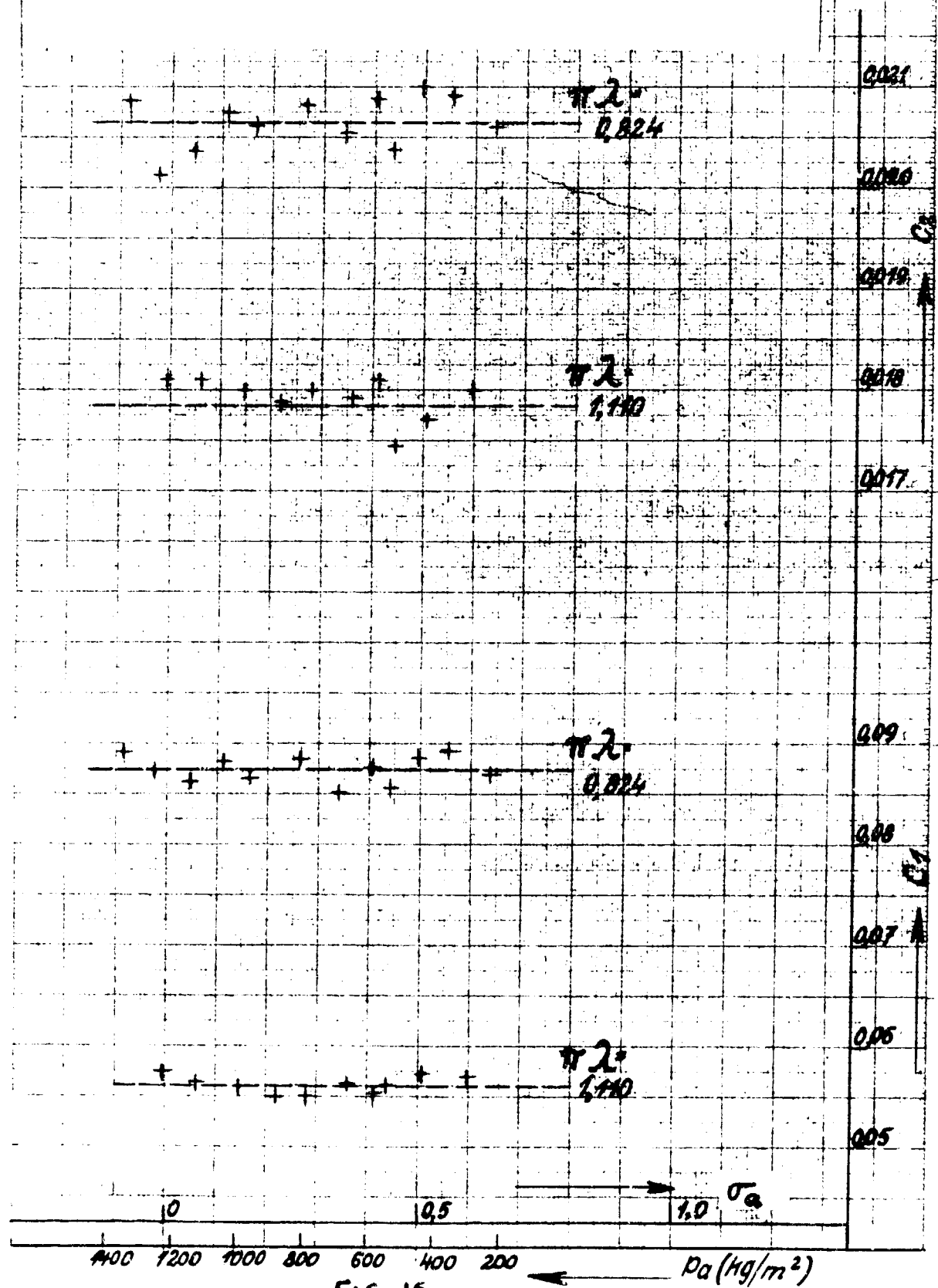


FIG. 16

SPEED COEFFICIENT FOR THE BEGINNING OF
AIR PRECIPITATION ON THE BLADE
PRECIPITATION VS PRESSURE p_q
 $v_a = 5.50 \text{ m/s.}$

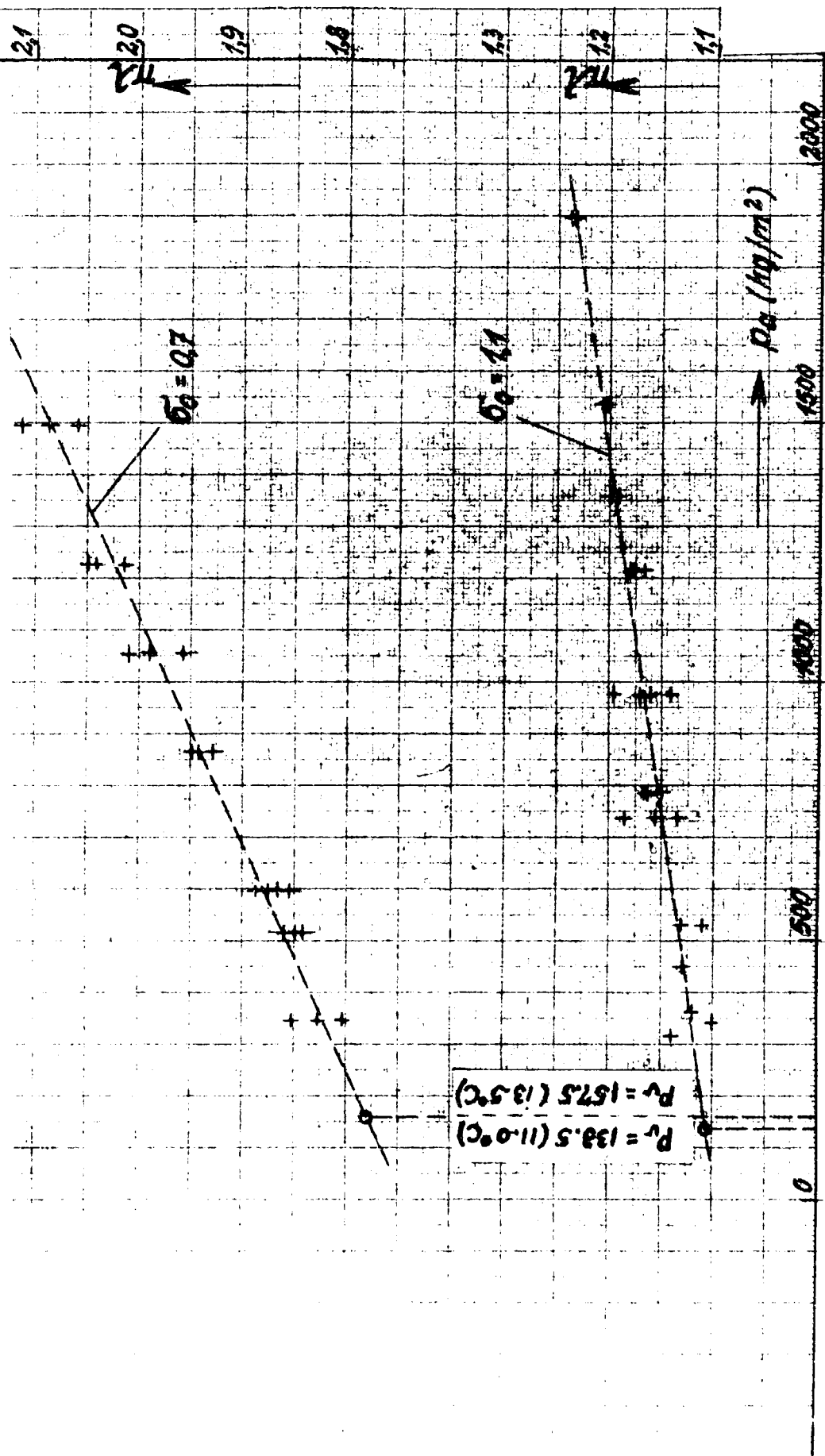


FIG. 17

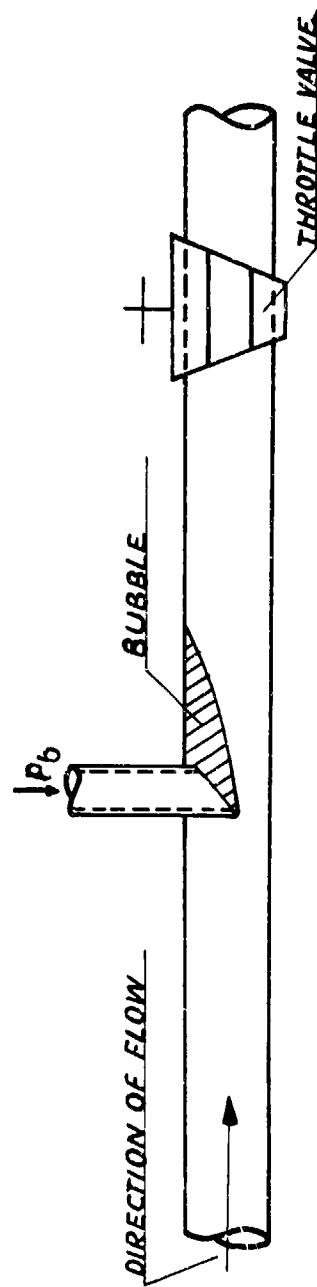


FIG. 18

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Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

No accurate method of measuring the absolute air content has been developed in Germany.

3. Influence of the Time Factor, Weber, Reynolds, and
Froude Numbers.

By using two different sized geometrically similar models and varying the water temperatures, Lerbs conducted tests at constant Reynolds and Froude numbers to determine the combined effect of the time factor, T.F., and the Weber number, W. The basic data from the curves of Fig. 19 were used for computing the variables, as follows:

v_a	t	d	F	10^6	\bar{R}	$10^5 K$	W	T.F.
m/sec	°C	m				m^3/sec^2		
5.00	37.3	0.2	3.57	0.692	1.45×10^6	7.04	7.1×10^4	0.040
6.125	11.0	0.3	3.57	1.270	1.45×10^6	7.40	15.2×10^4	0.049

Measurements at cavitation numbers $C_v = 1.1$ and 0.7 were carried out over a large range of the speed coefficient. The results, Fig. 20, indicate no influence of the two variables within the accuracy of the measurements. Since these two variables tend to produce opposite effects, it is possible that the influences cancel each other.

In order to determine the influence of the Reynolds number, Lerbs tested the same propeller of 0.2 meter diameter with the speed, cavitation number and Froude number constant, and with varying water temperatures. The conditions for the test were:

v_a	t	F	10^6	\bar{R}
m/sec	°C		m^2/sec	
5.50	11.2	3.93	1.265	0.87×10^6
5.50	31.6	3.93	0.778	1.42×10^6
5.50	51.2	3.93	0.536	2.05×10^6

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Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

The local cavitation number of a blade element at different angles of rotation depends on the Froude number, and can be expressed as,

$$\sigma_L = \frac{1}{1 + \lambda^2 / \lambda^2} \left(\sigma = \frac{\kappa \sin \Phi}{F^2} \right)$$

σ_L = local cavitation number

σ = cavitation number at the shaft center

$$\kappa = \frac{r}{R}$$

r = radius of the blade element

R = propeller radius

Φ = angular position of the blade from the horizontal

λ = speed coefficient $v_a / \pi n d$

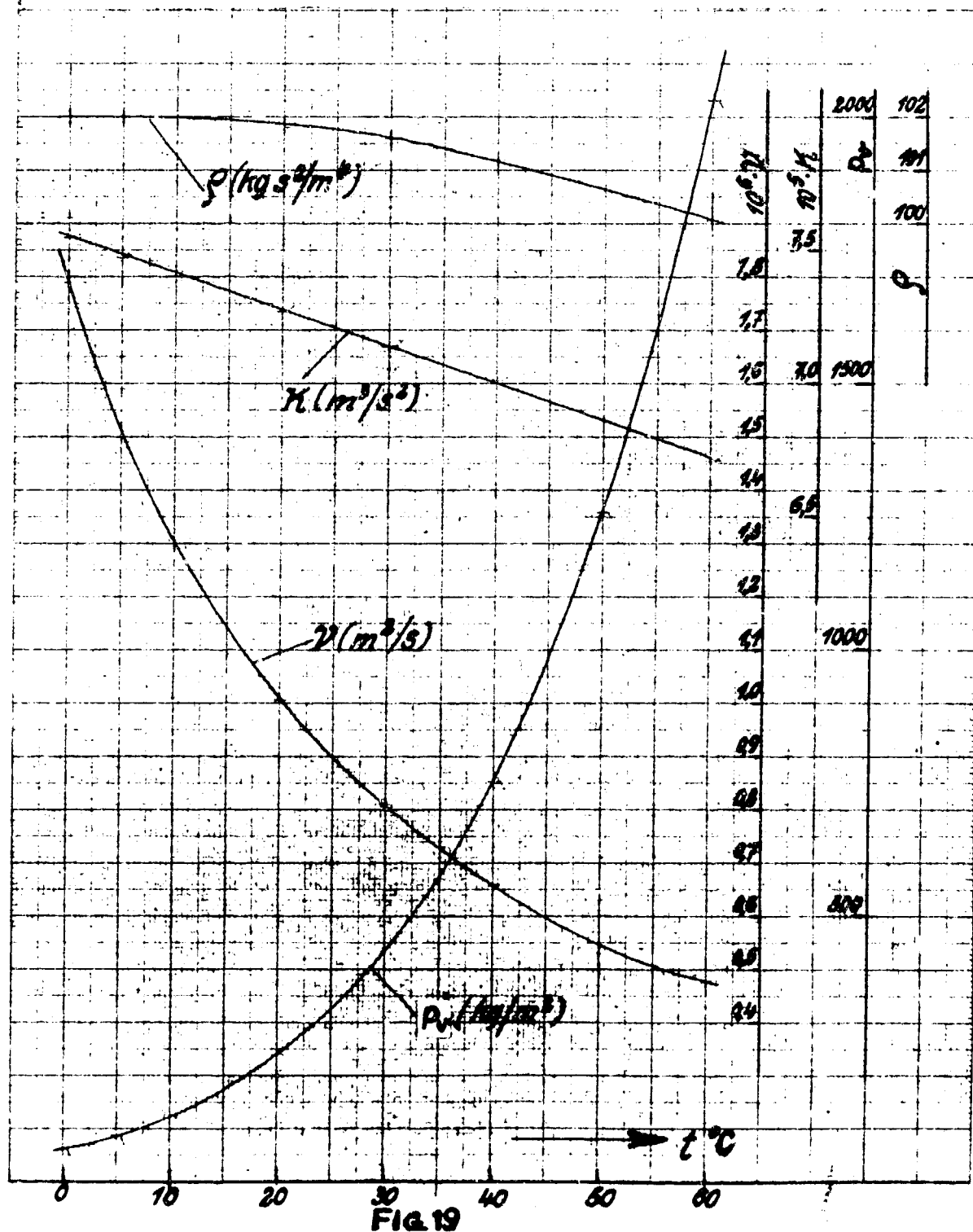
Since the greatest differences of local cavitation numbers between the full scale and model occur when the blade tip is in a vertical position, Lerbs uses the local cavitation number ratio for the vertical blade tip of full scale to model as a criterion of the difference of the Froude numbers, or,

$$\sigma_{L1} / \sigma_{L2} = (\sigma - 1 / F_1^2) / (\sigma - 1 / F_2^2), \text{ where the subscripts}$$

1 and 2 refer to the full scale and model, respectively. He further assumes that the variations of F used in the tests of Fig. 21 are the maximum allowable without influencing the coefficients of thrust and torque. Using the limiting lower values of $F_1 = 3.22$ and for the full scale and higher limit $F_2 = 5.00$ for the model, the values of σ_1 / σ_2 were plotted on the lower curve of Fig. 23. Similarly, by reversing the

PROPERTIES OF WATER

KINEMATIC CAPILLARITY $K = \eta/\rho$ DERIVED FROM LANDOLT-BÖRNSTEIN
 KINEMATIC VISCOSITY $\nu = \eta/\rho$ DERIVED FROM HANDBOOK OF
 DENSITY $\rho = \text{g}/\text{cm}^3$ DERIVED FROM HÜTTE, VOL. I EXPERIMENTAL PHYSICS
 VAPOR PRESSURE P_v DERIVED FROM HÜTTE VOL. I



σ, F, \bar{R} constant; W, T, F varied

d U_a t $Atm. p$ $\sigma = 1.1$ $\sigma = 0.7$
(m) (m/s) ($^{\circ}C$)

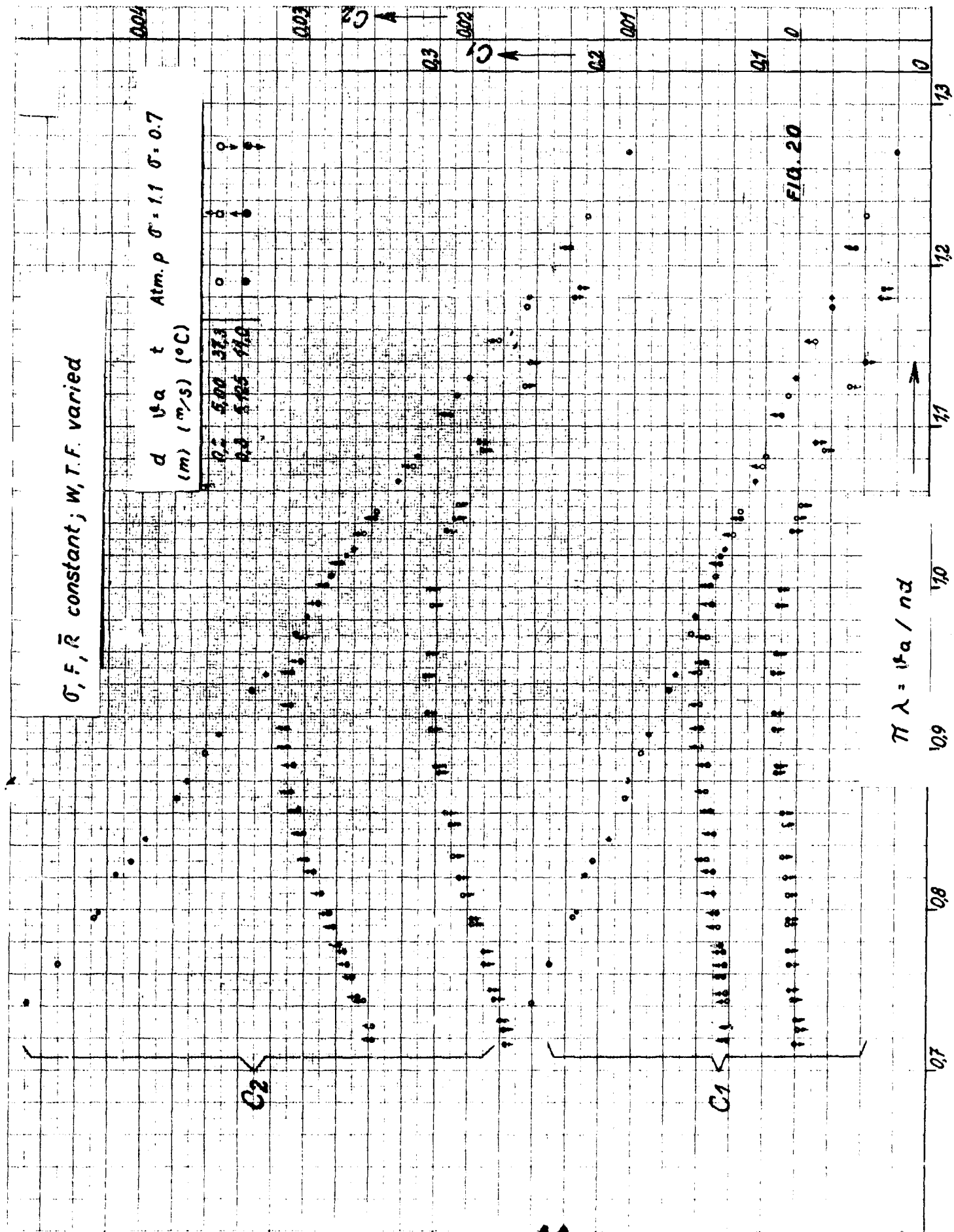
0.2	5.00	37.3		
0.3	5.25	44.0		

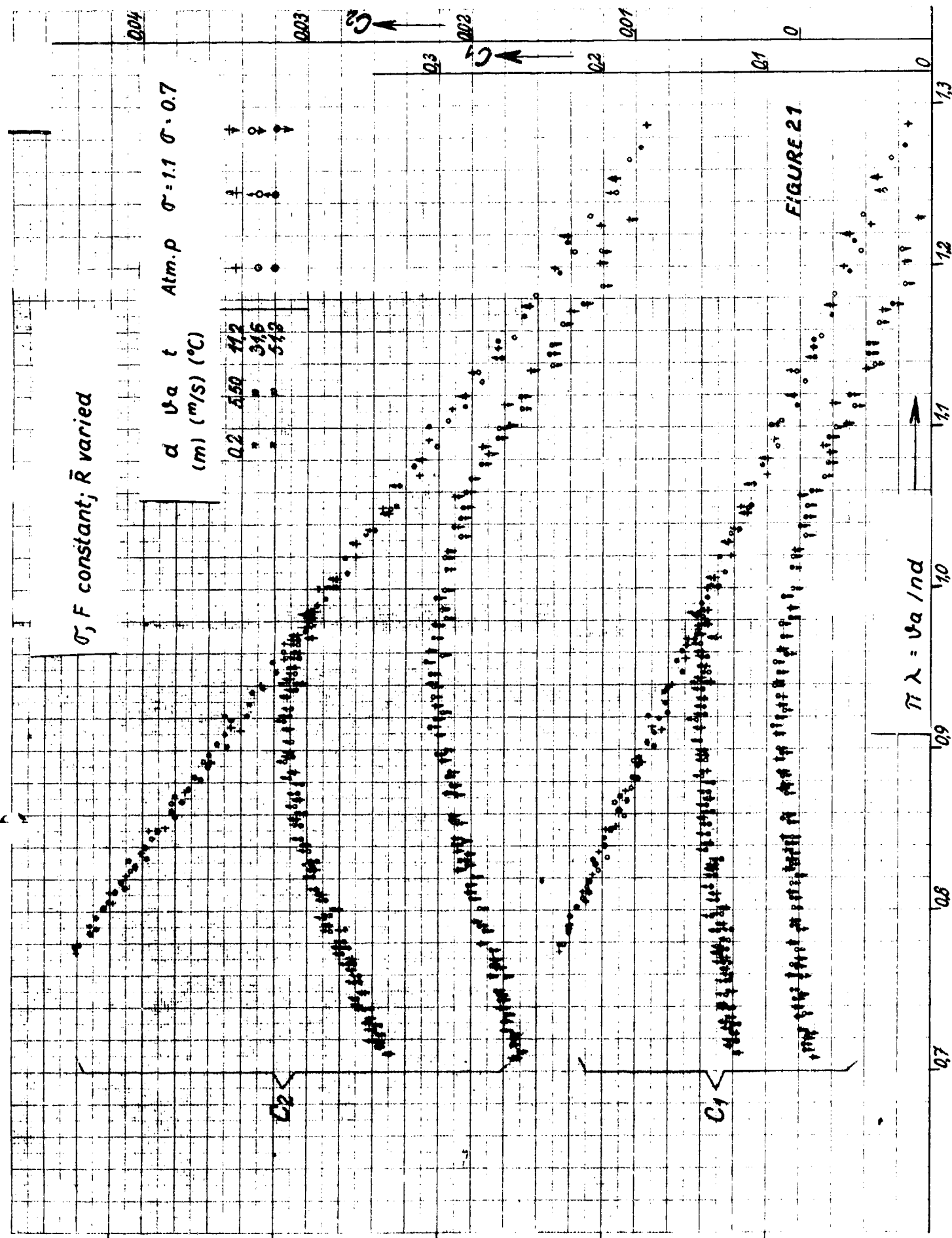
C_2

C_1

$$\pi \lambda = U_a / n \alpha$$

FIG. 20



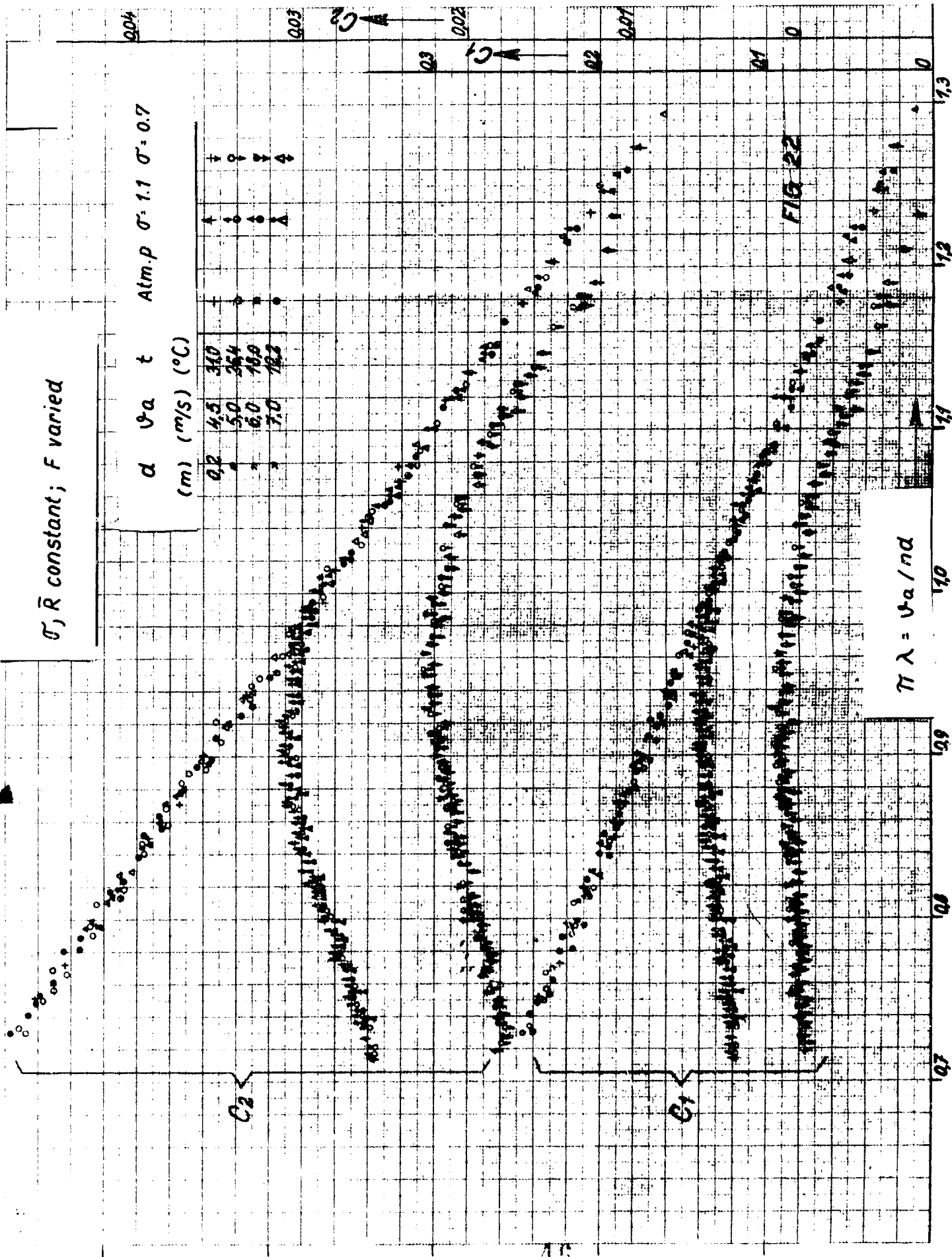


σ, \bar{R} constant; F varied

Atm. p $\sigma = 1.1$ $\sigma = 0.7$

d v_a t
(m) (m/s) ($^{\circ}\text{C}$)

0.2	4.5	310	+
0.2	5.0	364	+
0.2	6.0	409	+
0.2	7.0	482	+



ALLOWABLE VARIATION FOR THE FROUDE NUMBER CURVES OF EQUAL VALUES $\sigma_{L1} / \sigma_{L2}$

σ_{L1} - CAVITATION NUMBER AT FULL SCALE BLADE TIP IN THE VERTICAL POSITION

σ_{L2} = " " " MODEL " " " " " "

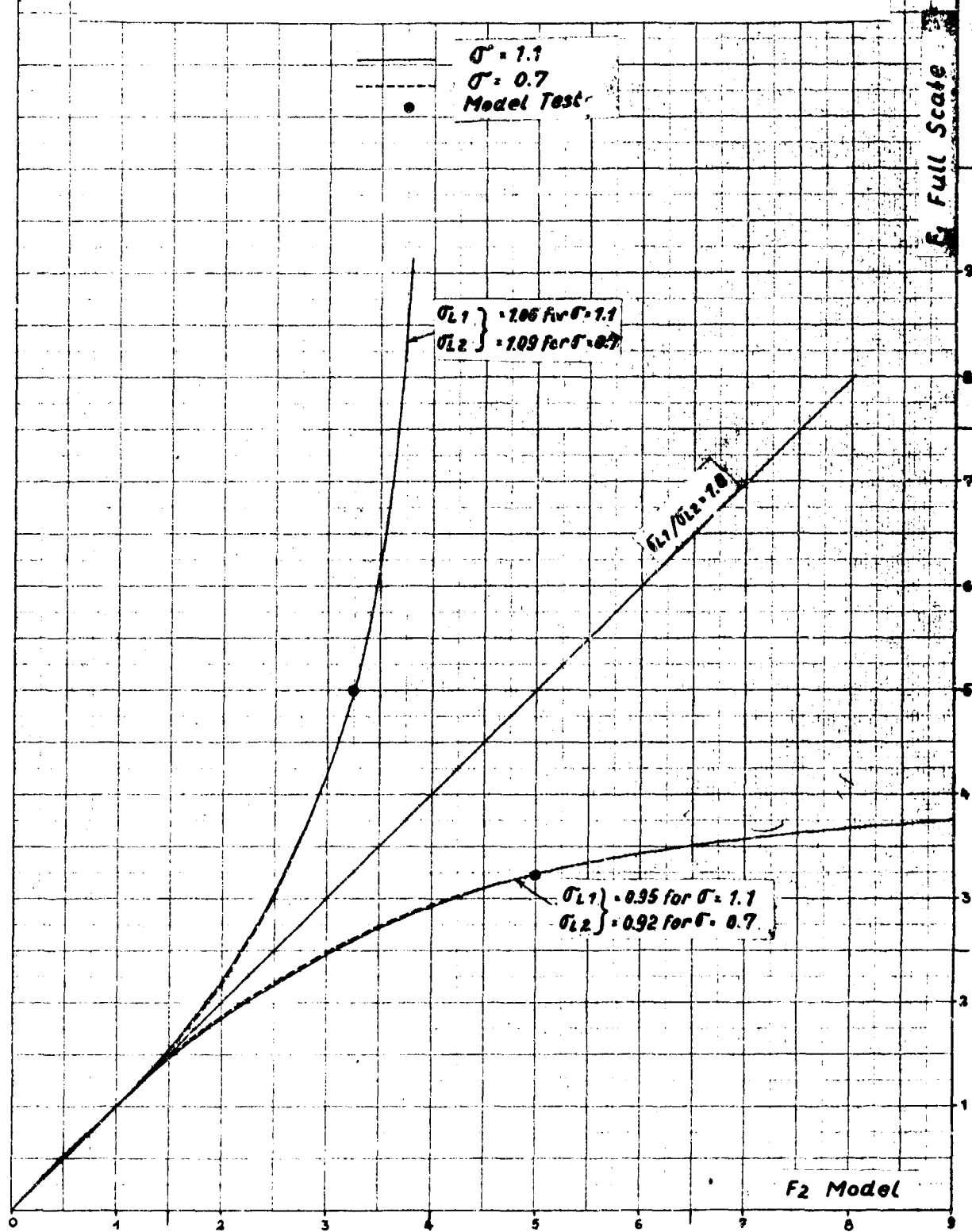


FIG. 23

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Cavitation Tunnel I of Hamburgische Schiffbau-
Versuchsanstalt, Cont'd.

limits, the upper curve was plotted. When these curves are entered with the Froude number for the full scale, F_1 , the model Froude number F_2 should lie somewhere between the upper and lower limiting curves, or $F_2 \min. \leq F_2 \leq F_2 \max.$

As a result of these tests for the influence of the basic variables, Lerbs has concluded that the test speed of advance can be chosen so that the Reynolds number is above the critical value 0.8×10^5 , and the Froude number is within the previously described limits. Therefore only the following variables are considered in a model cavitation test at Hamburg:

$$T = \rho n^2 d^4 C_1 (\lambda, \sigma) \quad \bar{R}_2 > \bar{R}_{\text{critical}}$$

$$M = \rho n^2 d^5 C_2 (\lambda, \sigma) \quad F_{2(\min)} \leq F_2 \leq F_{2\max.}$$

4. Model Test Calculation Compared with a Full Scale Trial.

A sample calculation by H.S.V.A. for the comparison of a model cavitation test to a full scale trial will be explained. The calculation illustrates the method only, since the ship characteristics are fictitious. A full scale trial of a twin screw ship at a displacement $\Delta = 525$ tons and with a water depth of 65 meters was compared with a model self-propulsion test with a corresponding $\Delta = 516$ tons and 63 meters water depth. The scale ratio of the full scale to the self-propulsion model was 18.

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Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

$$R_s = (R_m - R_{fm}) \frac{\rho_m}{\rho_s} \frac{R_{fs}}{R_{ms}}$$

$$R_{fm} = C_{fm} \frac{\rho_m}{2} S_m v_s^2$$

$$R_{fs} = C_{fs} \frac{\rho_s}{2} S_s v_s^2$$

$$R_{ms} = C_{ms} \frac{\rho_a}{2} A_s v_a^2$$

Subscripts m refer to the model.

Subscripts s refer to the full scale ship.

R_f = frictional resistance.

R_{ms} = air resistance of the ship.

C_f = friction coefficient.

ρ = mass density of water.

S = wetted surface area.

C_{ms} = coefficient of air resistance

ρ_a = mass density of air

A_s = projected area of the ship in the direction of the relative wind.

v_a = velocity of the relative wind.

The Prandtl-Schlichting friction formula was used for the smooth model and smooth ship.

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Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

Because of the difference in displacements for the full scale trial and the model test, the model thrust referring to the full scale trial was multiplied by $525/516 = 1.017$. The difference of the water depths was considered inconsequential.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
V_s	v_m	R_m	$R_m = v_m^2 l_m / \mu$	C_{fm}	T'_m / T_m	$1.017 T_m$	T'_m
knots	m/sec	kg				kg	kg
30.0	3.637	7.32	9.3×10^6	0.00306	1.13	3.22	3.65
32.5	3.939	8.30	10.1×10^6	0.00300	1.14	3.62	4.12
35.0	4.243	9.22	10.9×10^6	0.00295	1.15	4.02	4.63
37.5	4.544	10.22	11.6×10^6	0.00293	1.15	4.47	5.14
40.0	4.848	11.24	12.4×10^6	0.00291	1.16	4.90	5.66
42.5	5.150	12.26	13.2×10^6	0.00288	1.16	5.33	6.20
45.0	5.454	13.38	14.0×10^6	0.00286	1.16	5.79	6.72

The cavitation test speed was to be chosen so that \bar{R}_2

\bar{R}_{crit} and $F_2(\min) \leq F_2 \leq F_2(\max)$. To determine this, the cavitation number for the shaft center, -, and the full scale Froude number, F_1 , must be calculated. In determining the static pressure for calculating \bar{R} in this example, the dynamic influences, as well as the atmospheric pressure and the pressure at rest due to the shaft depth were considered. By mounting a pitot tube at the shaft center of the underway model and another in the undisturbed flow, the pressure difference

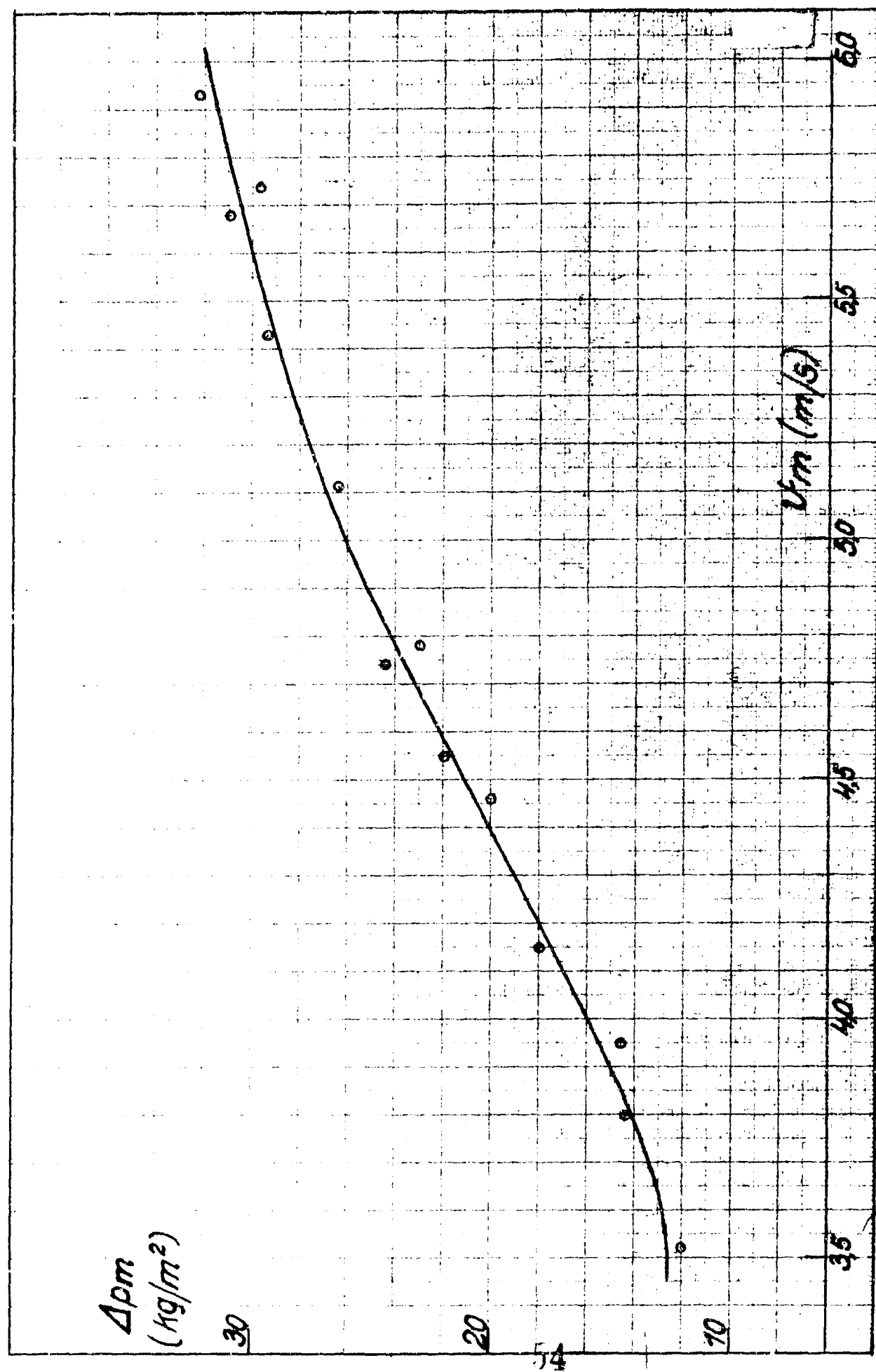


FIG.24

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Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

Column (5) is the numerator of the cavitation number, with barometric pressure $P_B = 10330 \text{ kg/m}^2$ and vapor pressure

$$P_v = 200 \text{ kg/m}^2 \text{ at } 17^\circ\text{C. Thus } P_B + \rho_s h_s - P_v = 10130 + \rho_s h_s \text{ (kg/m}^2\text{)}$$

Column (6) is the cavitation number denominator.

$$\rho_s / 2 v_s^2 (1-w)^2 = \rho_s / 2 v_{am}^2 = 1.015 \cdot 51.18 v_{am}^2 = 933 v_{am}^2 \text{ (kg/m}^2\text{)}.$$

The speed of advance for the cavitation test was chosen as 5.5 m/sec. The full scale Froude number was calculated by the formula

$$F_1 = \frac{v_s (1-w)}{\sqrt{g d_s}} = \frac{v_{am}}{\sqrt{g d_m}} \text{ with } d_m = d_s / 18 = 0.111 \text{ m.}$$

The scale ratio for the propulsion test was 18, but for the cavitation test, a larger propeller of scale ratio $\lambda = 9.09$ was used. Thus, the cavitation model Froude number, F_2

$$F_2 = \frac{v_{ac}}{\sqrt{g d_c}} \text{ where the diameter of the cavitation test pro-}$$

peller, $d_c = d_s / \lambda_c = 0.220 \text{ m.}$

d_s = diameter of the ship propeller, and subscript c refers to the cavitation model propeller.

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Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

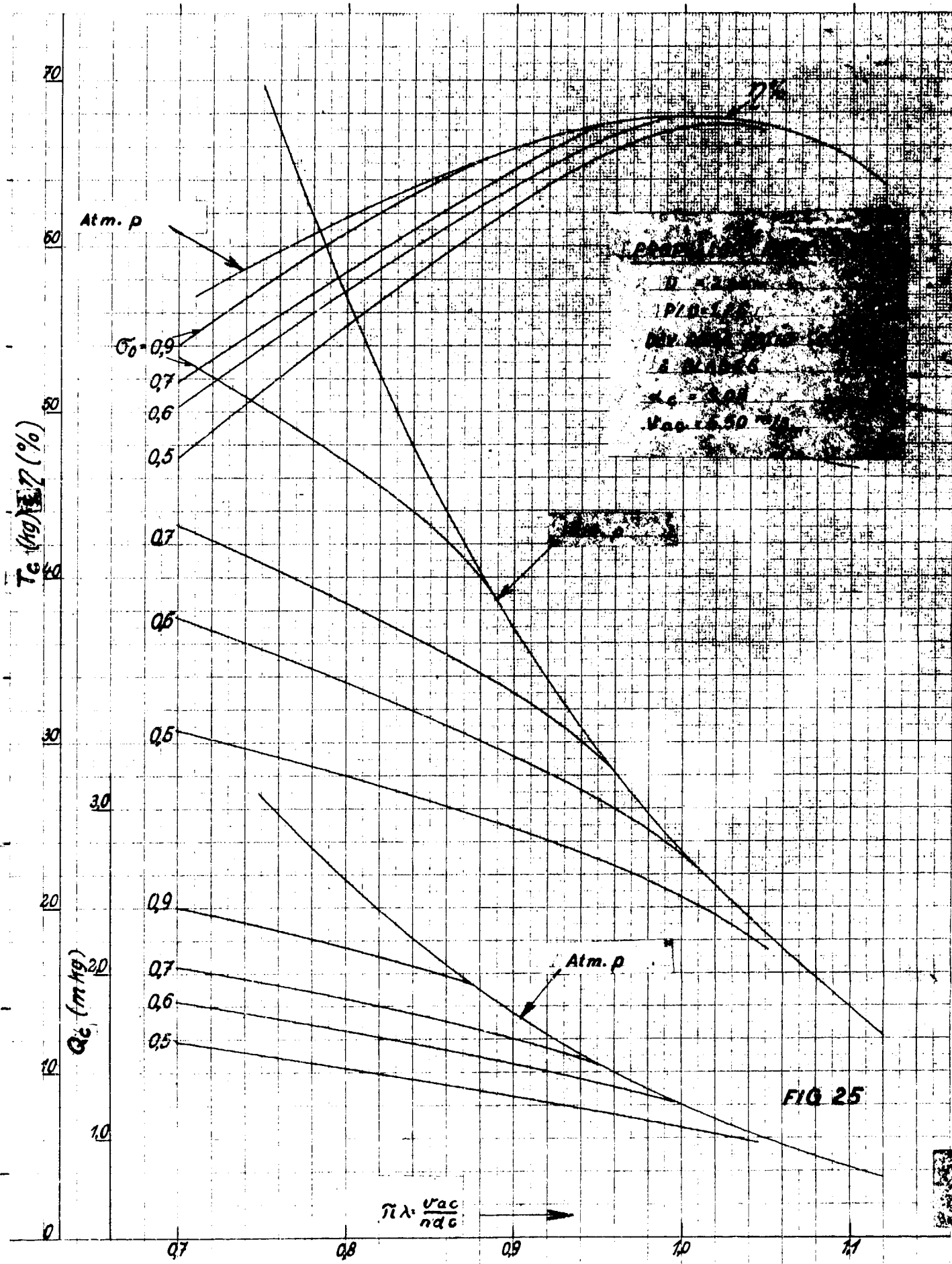
(1)	(2)	(3)	(4)
V_s knots	v_{am} m/sec	$(5.50/v_{am})^2$	T_c kg
30.0	3.437	2.560	36.68
32.5	3.683	2.229	36.00
35.0	3.946	1.943	35.28
37.5	4.203	1.713	34.52
40.0	4.460	1.520	33.74
42.5	4.712	1.362	33.12
45.0	4.936	1.241	32.72

Fig. 25 shows the direct measurement results of the cavitation characterization test. The full scale revolutions per minute, N_s , can be calculated from the ratio, $\frac{v_{am}}{T_c}$, determined by entering the curves with the proper cavitation number, σ , and the corresponding calculated thrust, T . To obtain a more exact interpolation, the measured thrust T_c was replotted with $\frac{v_{am}}{T_c}$ as abscissa and σ as the parameter (Fig. 26). The value of σ in column (4) below was obtained from the curves of Fig. 26.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
V_s knots	T_c kg	σ	$\pi \lambda$	N_s min ⁻¹	Q_c m.kg.	S.H.P.	η %	η %
30	36.68	1.088	0.901	485	1.76	6390	65.4	65.1
32.5	36.00	0.950	0.905	518	1.73	7700	65.6	65.2
35.0	35.28	0.832	0.908	554	1.70	9290	65.7	65.4
37.5	34.52	0.737	0.896	597	1.66	11070	64.9	64.6
40.0	33.74	0.657	0.858	662	1.65	13740	61.1	60.9
42.5	33.12	0.591	0.802	478	1.63	17150	56.8	56.4
45.0	32.72	0.540	0.732	859	1.63	21600	51.1	51.1

In column (5); $N_s = 60 \frac{v_{am}}{T_c} \sqrt{\frac{d_s}{\pi \lambda}} = 127.3 \frac{v_{am}}{T_c} \sqrt{\frac{d_s}{\pi \lambda}}$

In column (7); SHP = $N_s \frac{Q_c}{30.75}$, where



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Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

$$Q_s = C_2 / s (N_s/60)^2 d_s^5,$$

$$C_2 = Q_c / \left(\frac{N_c}{60} \right)^2 d_c^5, \text{ and}$$

N_c = RPM of cavitation model.

$$\text{Then SHP} = \left(\frac{T}{30.75} \frac{s}{C_2} \times c^5 \right) \left(\frac{N_s}{N_c} \right)^2 N_s Q_c$$

$$\text{Since } N_c/60 = v_{ac}/\pi d_c \text{ and } N_s/60 = v_{am}/\pi d_s$$

$$\text{Then } \left(\frac{N_s}{N_c} \right)^2 = (v_{am}/v_{ac})^2 \left(\frac{d_m}{d_c} \right)^2$$

$$\begin{aligned} \text{Therefore SHP} &= \left(\frac{T}{30.75} \frac{s}{C_2} \frac{3}{c^5} \right) \left(\frac{v_{am}}{v_{ac}} \right)^2 N_s Q_c \\ &= 0.633 v_{am}^2 N_s Q_c \end{aligned}$$

In column (6), the value of Q_c was obtained from the cavitation characterization curves replotted with Q_c as ordinate, η as absciss, and η as the parameter (Fig. 27).

In column (8) the efficiency was determined as follows:

$$\eta = 60 T_s v_{as}/s \cdot 2 \pi N_s = \lambda d_s T_s / 2 Q_s$$

$$T_s/w_s = C_1/C_2 \cdot d_s = T_c/Q_c \cdot c$$

$$\text{Thus } \eta = \frac{\lambda T_c d_s}{2 Q_c c} = 0.0350 \frac{\pi \lambda T_c}{Q_c}$$

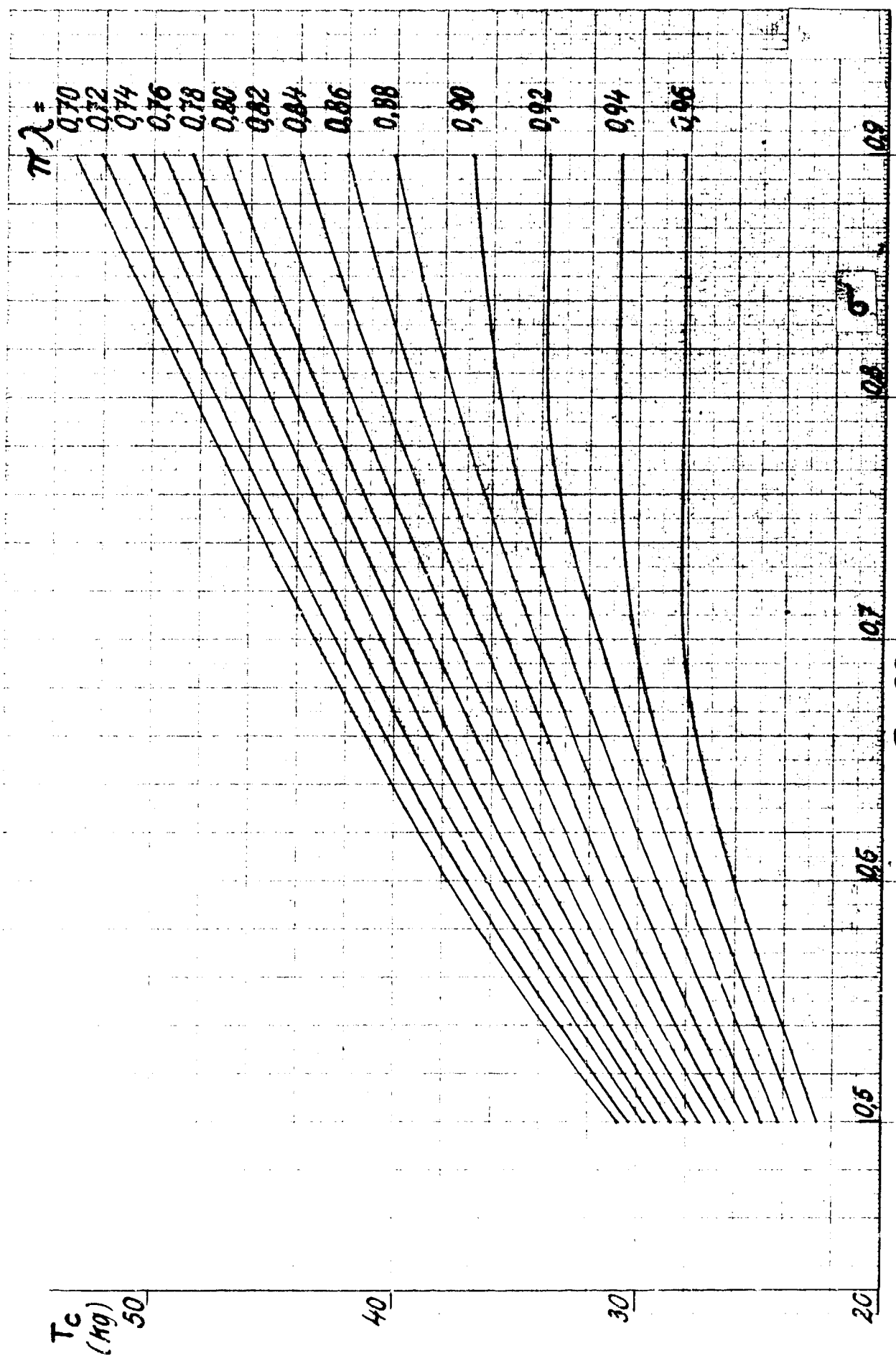


Fig 26

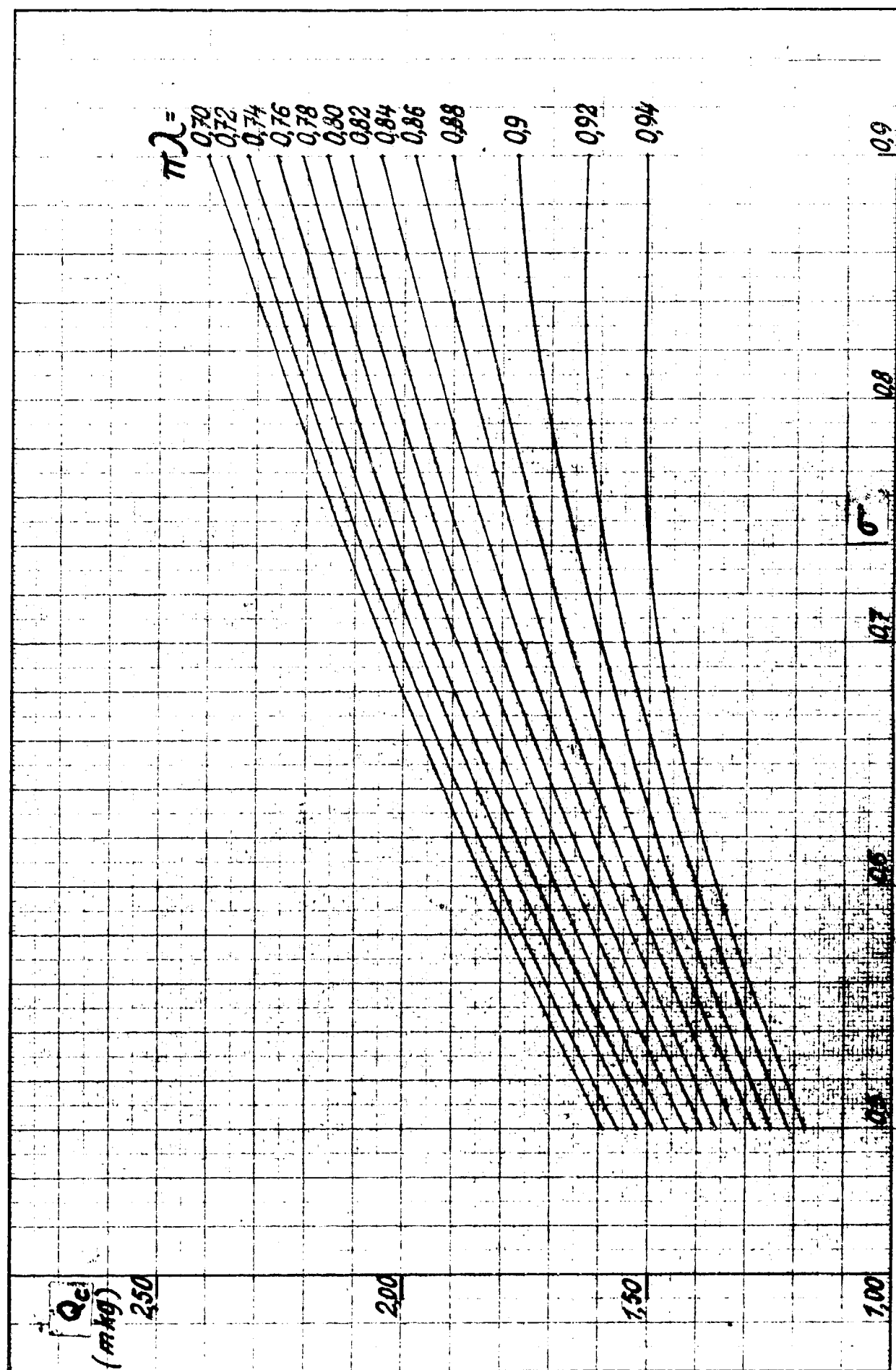


FIG. 27

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Cavitation Tunnel I of Hamburgische Schiffbau
Versuchsanstalt, Cont'd.

In column (9) the efficiency was recalculated by using the thrust T'_m and the SHP of column (7).

$$\eta = \frac{T'_m \cdot m^3 \cdot v_{am} \cdot \sqrt{m}}{75 \text{ SHP}} = \frac{331.0 T'_m v_{am}}{\text{SHP}}$$

Fig. 28 shows the comparison of the cavitation test results with the sample full scale trial results. Since a portion of the data used was fictitious, the average error between model and full scale results of about 2 percent is not indicative of the average error of actual tests at Hamburg.

Very few cavitation tests for comparison of model tests to full scale trial results were performed in the Hamburg tunnel, since trial results of naval vessels were seldom made available to the tank personnel. Ordinarily, propeller cavitation characterization data was forwarded to O.K.M. 7 and the Navy personnel made their own analysis of model and full scale test results.

III. Cavitation Tunnel II at Hamburgische Schiffbau
Versuchsanstalt.

A. Purpose

During the final preparations for World War II, the need arose for a new large cavitation tunnel at the Hamburg Model Basin to be used for the following work:

- (1) cavitation tests of full scale torpedo propellers, both single screw and contra-turning,
- (2) propulsion tests at reduced pressure of complete ship model forms mounted in the test section in order to obtain actual flow conditions at the propellers,

⁷Oberkommando der Kriegsmarine.

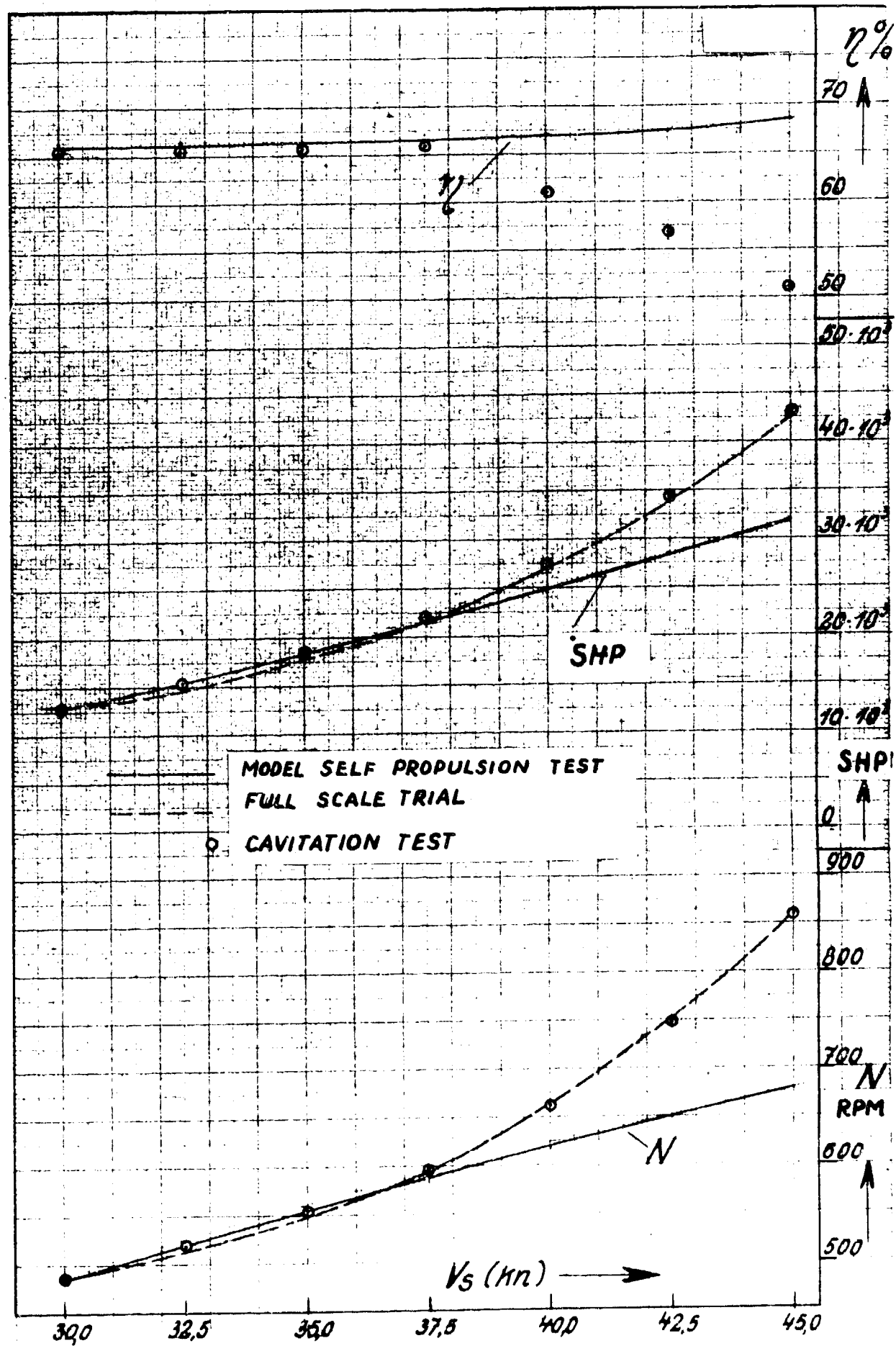


FIG. 28

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Cavitation Tunnel II at Hamburgische
Schiffbau Versuchsanstalt, Cont'd.

- (3) propeller scale effect tests,
- (4) routine propeller cavitation characterization tests, and
- (5) tests of special devices, such as sound domes.

Since the new tunnel was intended primarily for propeller studies and tests, the design followed closely the features of the first Hamburg cavitation tunnel as it was finally altered.

B. Tunnel Description and Principal Characteristics.

Construction of the world's largest cavitation tunnel was started at H.S.V.A. in 1939. The shipbuilding firm, Blohm and Voss in Hamburg, fabricated the all-welded tunnel structure from shipbuilding steel. The elbow aft of the test section was divided and had a large radius of curvature similar to the design of the smaller cavitation tunnel. Instruments were procured or manufactured by H.S.V.A.

The new cavitation tunnel, shown diagrammatically in Fig. 29, has the following principal characteristics:

Test section

Height	1.2 meters (47.24 in.)
Width	2.4 meters (94.49 in.)
Length	5.3 meters (208.66 in.)
Maximum velocity	8 m/sec (16 knots)

Vertical height between upper and lower legs 9 m. (32.8ft)

Driving motor

Horsepower	400 H.P.
RPM	1000
Voltage	0 to 440 V. D.C.

Propeller pump RPM 250

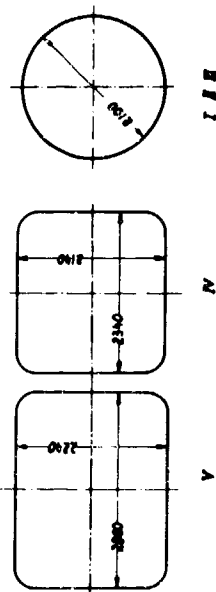
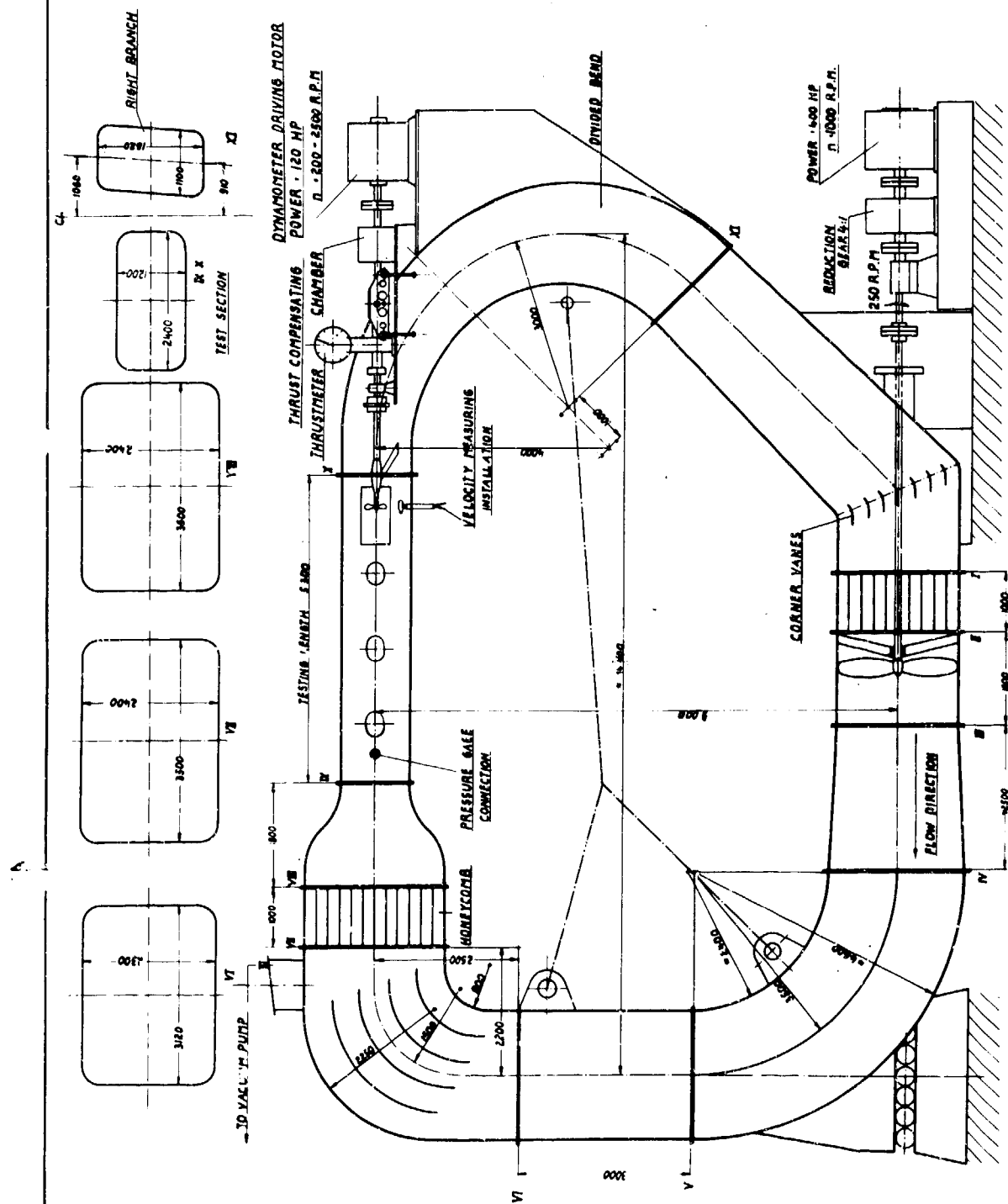


FIGURE 29
H.S.V.A. CAVITATION TUNNEL II
DIAGRAMMATIC SKETCH
 ALL MEASUREMENTS IN MILLIMETERS

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Cavitation Tunnel II at Hamburgische
Schiffbau Versuchsanstalt, Cont'd.

Propeller dynamometer

Horsepower (max.) 120
RPM 200 to 2500
Maximum thrust 1000 kg (2200 lbs.)

Main vacuum pump

Horsepower 2.5
Capacity $50\text{m}^3/\text{hr.}$

Auxiliary vacuum pump

Horsepower 0.75
Capacity $15\text{m}^3/\text{hr.}$

The test section of the tunnel was made unusually long to permit the insertion of ship model forms for propeller cavitation tests under actual conditions of variable wake and angular flow. Fig. 30 shows the upper section of the tunnel including the nozzle, test section, and the divided elbow downstream from the test section. The close-up view of the test section in Fig. 31 shows the large observation window and the small windows on each side of the test section for permitting good visual observation and sufficient light for photography.

The lower sections of the tunnel are shown in Fig. 32 and 33. The driving motor supported on a fixed foundation, (Fig. 34) has an independent forced-air circulation system for cooling. To allow for the expansion or contraction of the tunnel with changes in temperature, the structure is supported on seven large rollers of 0.35 meter (13.8 inches) diameter at the end opposite the driving motor (Fig. 35).

The arrangement of guide vanes and honeycombs is illustrated in Fig. 29. No vanes are used in the large radius bend at the dynamometer, a cascade of short vanes is used at the driving motor corner, a single long vane with a well-rounded bend is used at the lower left corner, and four circular arc guide vanes are used in the upper corner next to the nozzle.

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Cavitation Tunnel II at Hamburgische
Schiffbau Versuchsanstalt, Cont'd.



Fig. 30

H.S.V.A. CAVITATION TUNNEL II, JUNE 1945.
VIEW OF UPPER LEVEL.

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Cavitation Tunnel II at Hamburgische
Schiffbau Versuchsanstalt, Cont'd.

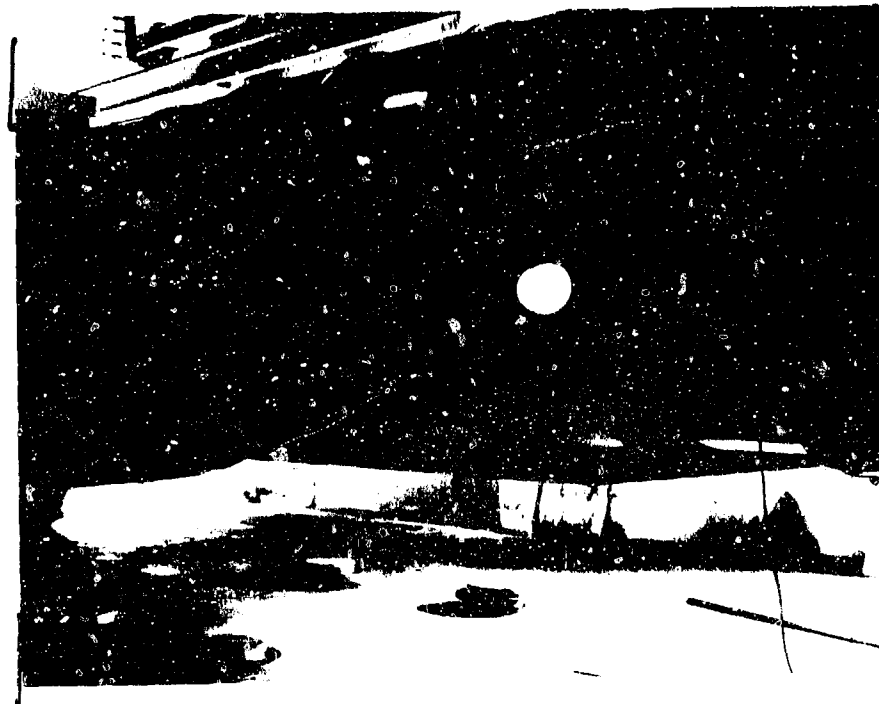


Fig. 31

H.S.V.A. CAVITATION TUNNEL II, JUNE 1945.
CLOSE-UP VIEW OF THE TEST SECTION.

The small window in the panel adjacent to the large window is covered with a sheet metal plate.

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Cavitation Tunnel II at Hamburgische
Schiffbau Versuchsanstalt, Cont'd.

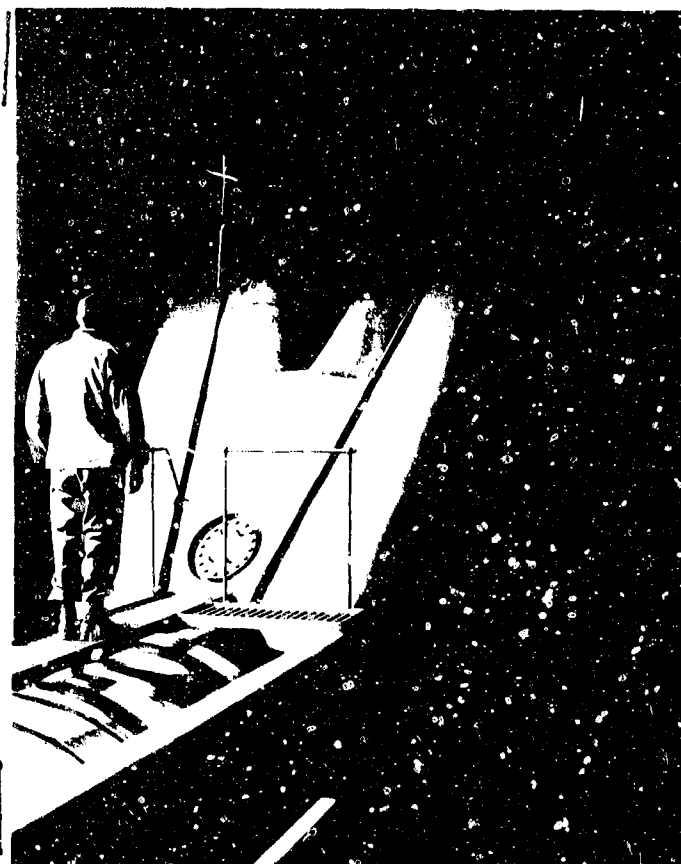


Fig. 32

H.S.V.A. CAVITATION TUNNEL II, JUNE 1945.

The vertical, rectangular shaped divided sections converge above the lower horizontal section at the driving motor end. The lower horizontal section is circular in way of the propeller pump.

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Cavitation Tunnel II at Hamburgische
Schiffbau Versuchsanstalt, Cont'd.



Fig. 33.

H.S.V.A. CAVITATION TUNNEL II, JUNE 1945.

The cross-section of the tunnel changes from circular in the lower horizontal leg to rectangular in the vertical leg leading to the nozzle.

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Cavitation Tunnel II at Hamburgische
Schiffbau Versuchsanstalt, Cont'd.



Fig. 34

H.S.V.A. CAVITATION TUNNEL II, JUNE 1945.

DRIVING MOTOR AND REDUCTION GEAR

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Cavitation Tunnel II at Hamburgische
Schiffbau Versuchsanstalt, Cont'd.



Fig. 35

H.S.V.A. CAVITATION TUNNEL II, JUNE 1945.

Roller arrangement to Allow for Expansion of the Tunnel
Structure.

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Cavitation Tunnel II at Hamburgische
Schiffbau Versuchsanstalt, Cont'd.

Honeycombs for straightening the flow are installed in front of the propeller pump and just before the nozzle contraction.

Two special boilers in an adjacent room can provide warm water up to about 60°C (140°F) for filling the tunnel in order to obtain lower cavitation numbers and conduct basic research tests. To minimize heat transfer from the tunnel to the room, the tunnel was intended to be completely insulated by the use of fibre glass bats and light metal sheathing installed between the webs of the tunnel structure. Fig. 30 to 33, inclusive, indicate that this work was only partially completed in June, 1945.

The complete power requirements for the large tunnel are provided from a new 600 H.P., 220 volt A.C. generator in the power station. The speed of the impeller motor drive and the propeller dynamometer drive are controlled by Ward-Leonard systems.

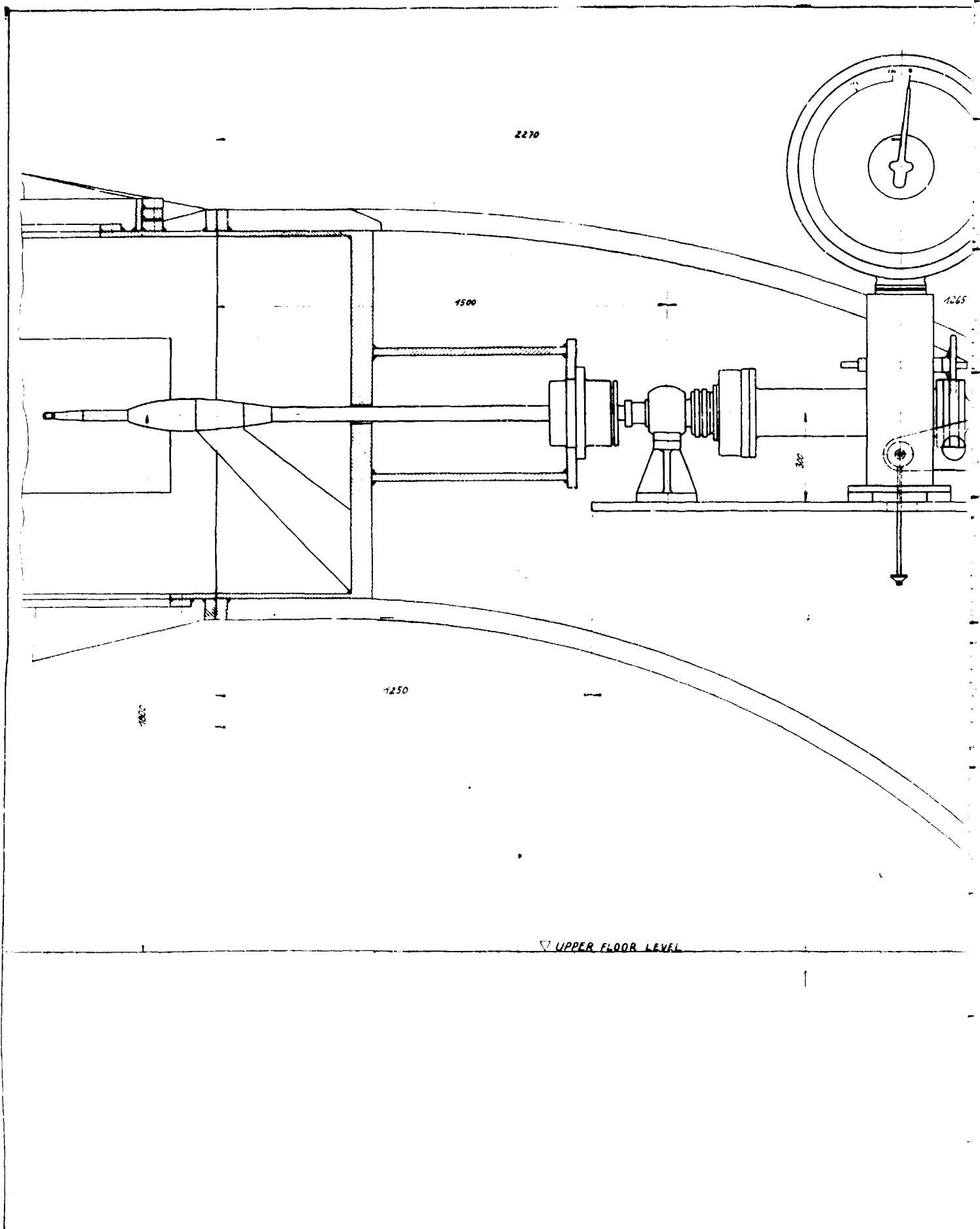
The interior of the tunnel is painted with the same special chloro-latex paint used in cavitation tunnel I.

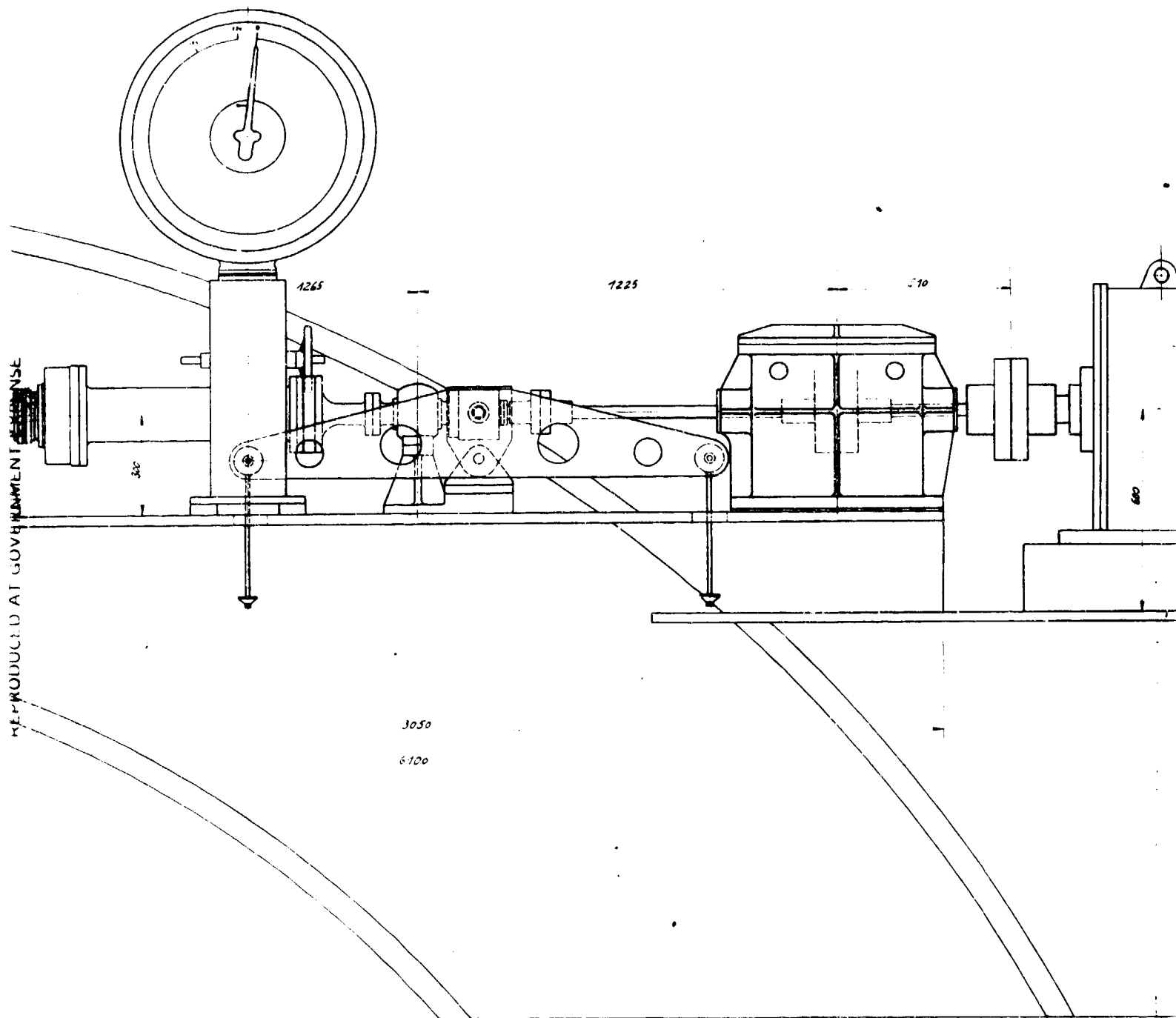
C. Measuring Instruments.

1. Propeller Dynamometer Arrangement.

The propeller dynamometer driving arrangement shown in Fig. 36 is very similar in principal to the final altered arrangement of cavitation tunnel I. A compensating chamber evacuated by a separate vacuum pump, compensates for the thrust correction due to the pressure difference between the tunnel interior and the atmosphere. No automatic pressure control device was installed to maintain equality of pressure in the tunnel and the compensating chamber because of the unsatisfactory operation of the apparatus installed on the old tunnel. (Fig. 6). However, Dr. Lerbs stated that the compensating chamber method of eliminating the thrust

NOT PRODUCED AT GOVERNMENT EXPENSE





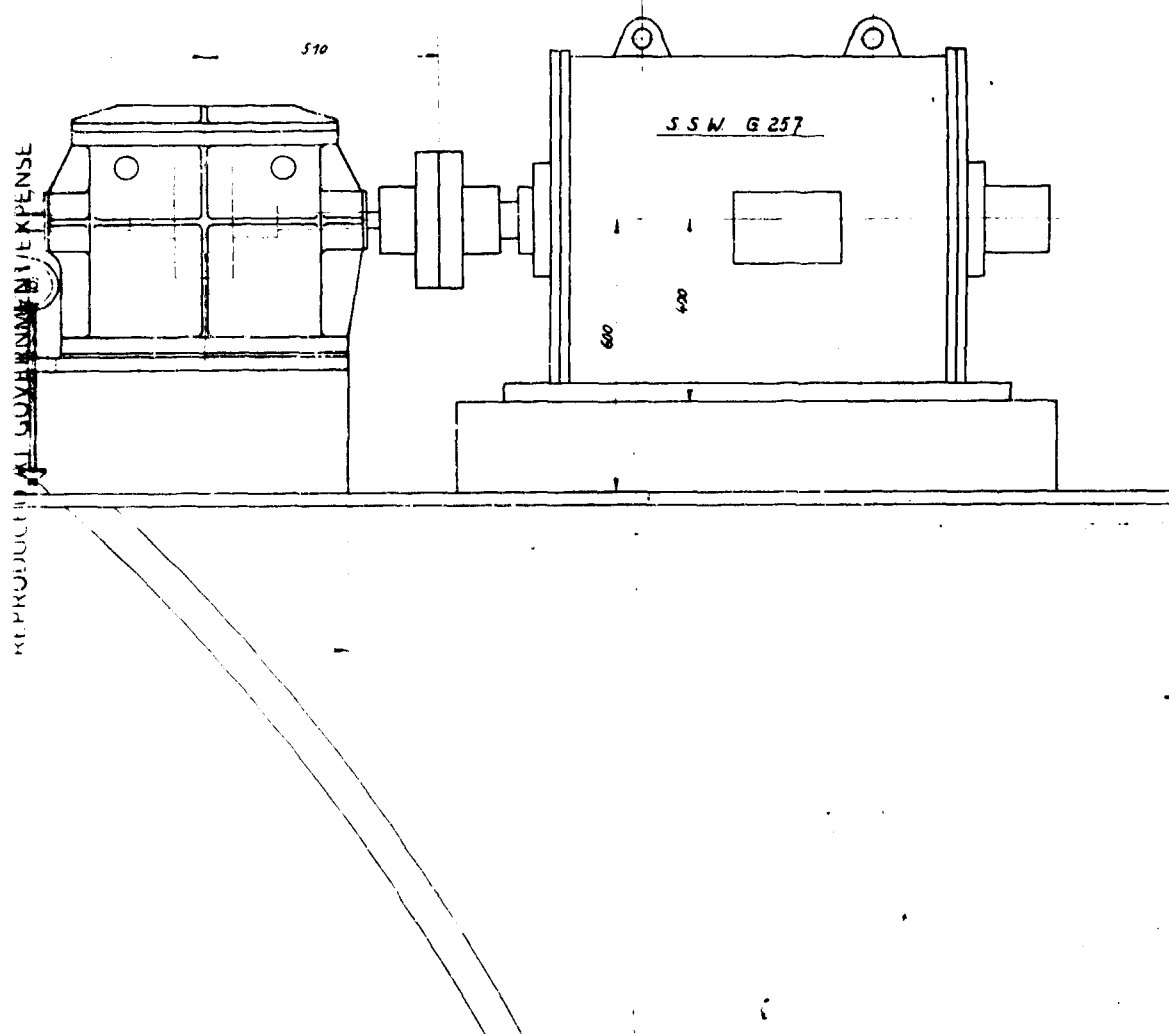


FIG. 36

PROPELLER DYNAMOMETER

ARRANGEMENT

H.S.V.A. CAVITATION TUNNEL II

RESTRICTED.

Cavitation Tunnel II at Hamburgische
Schiffbau Versuchsanstalt, Cont'd.

correction correction was advantageous only if an automatic regulating device was also used. Therefore he intended to develop a more satisfactory automatic device for the large tunnel.

The sectional view of the dynamometer apparatus, Fig. 37, shows the double shaft arrangement, the thrust balance, and the calibrated torsion rod arrangement, which are similar to the final installations for cavitation tunnel I as described in Part II. Grease is used to lubricate the outer shaft bearings and to seal the stuffing box between the Buna rubber seals. The main stuffing box and bearing installation is cooled by a water jacket. The torque is measured by a potentiometer and "cross-spool", or balanced bridge instrument shown schematically in Fig. 4. Several sizes of torsion rods are used to cover the complete measuring range of the dynamometer. For calibrating the torsion rods, the apparatus shown in Fig. 38 is mounted on the propeller shaft in place of the model propeller, and weights are suspended from the arms.

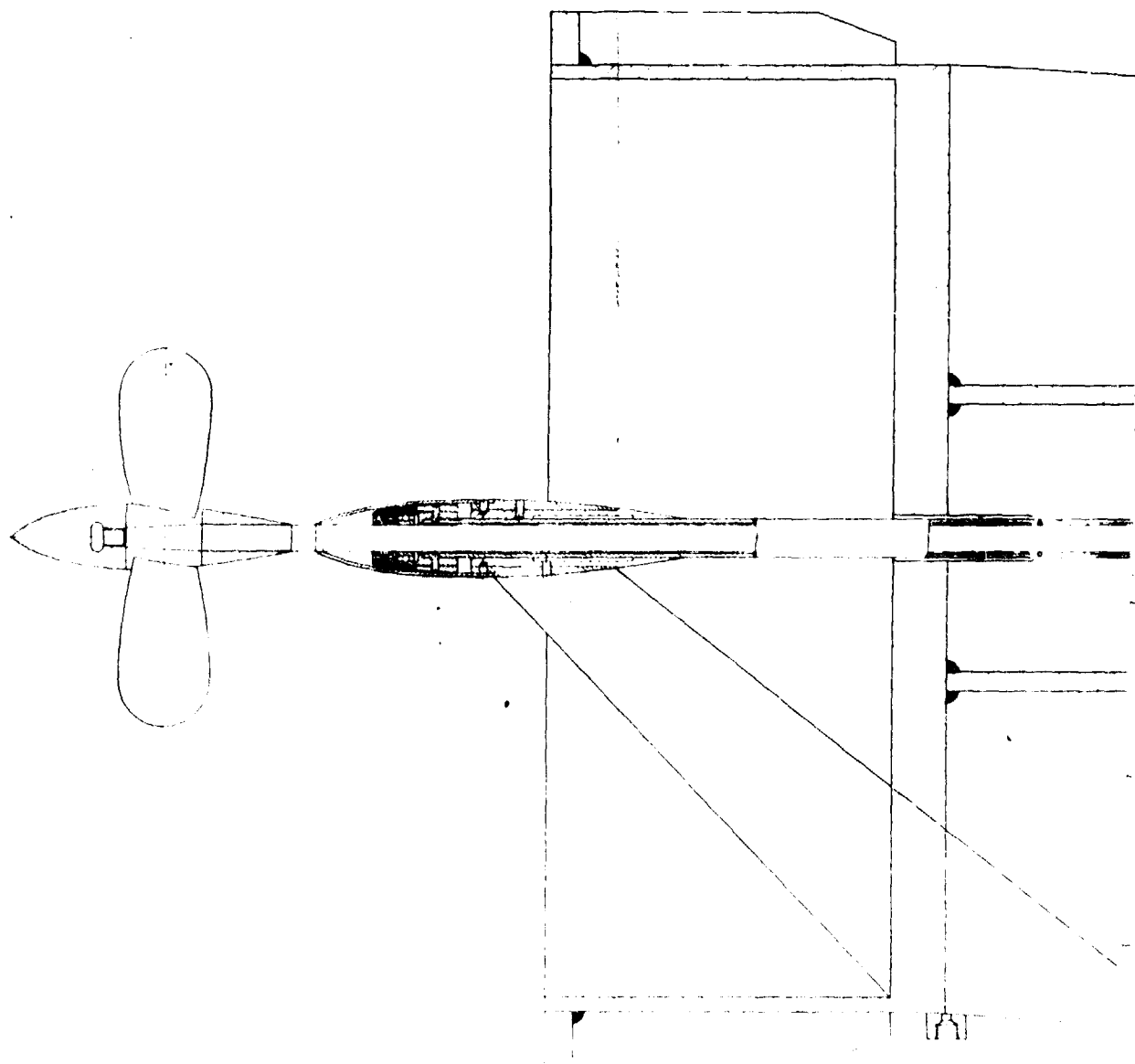
The thrustmeter was actually installed on the end of the thrust balance arm next to the pressure compensating chamber instead of the tunnel end as shown in Fig. 37. The final arrangement of the dynamometer apparatus as of June 1945 is shown in Fig. 39.

The water speed is measured by a pitot tube in the bottom of the test section in the plane of the propeller, (Fig. 38). Static pressure is measured from a pressure tap on the side of the test section at the height of the shaft center.

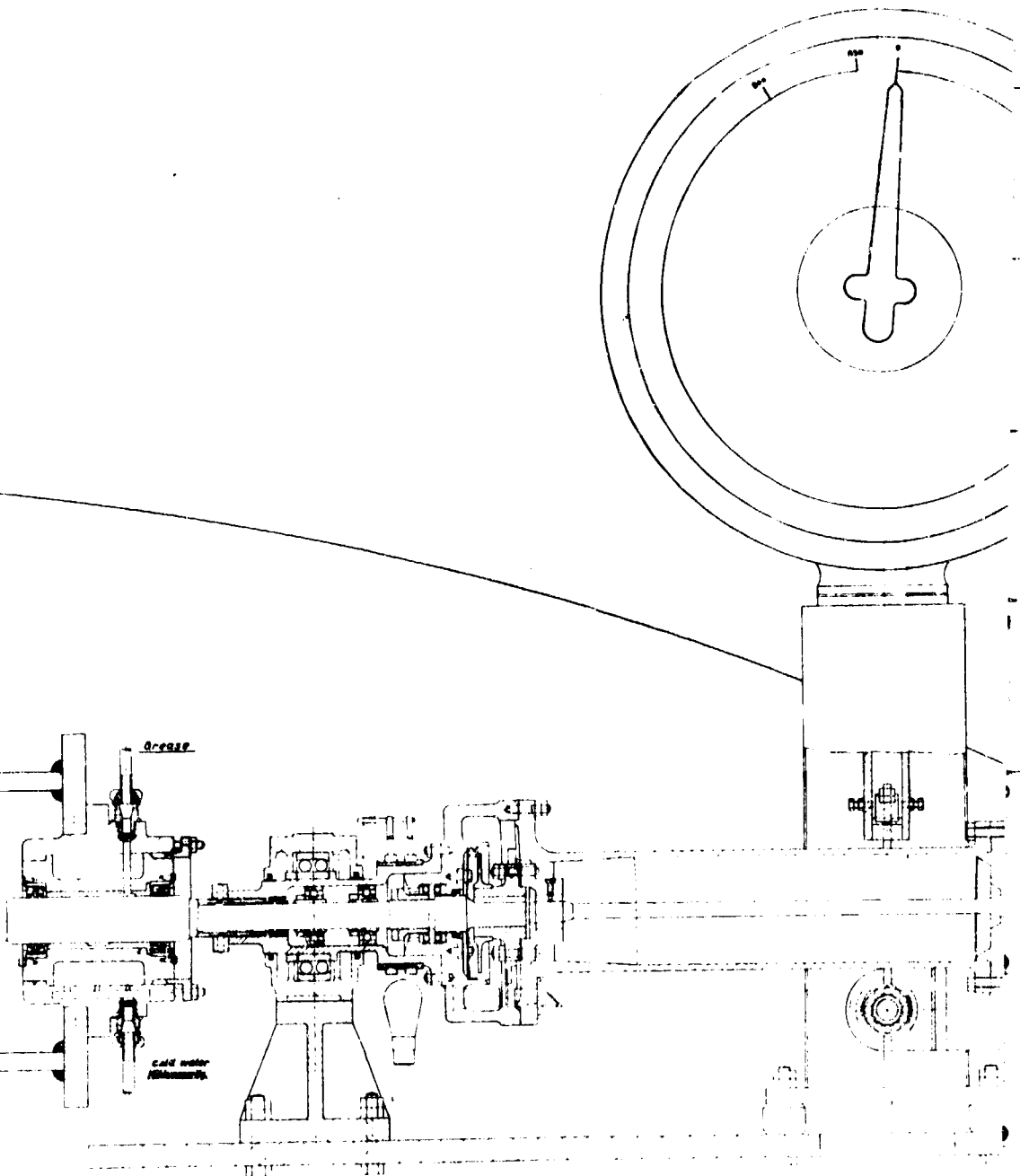
2. Testing arrangement for Complete Ship Model Forms.

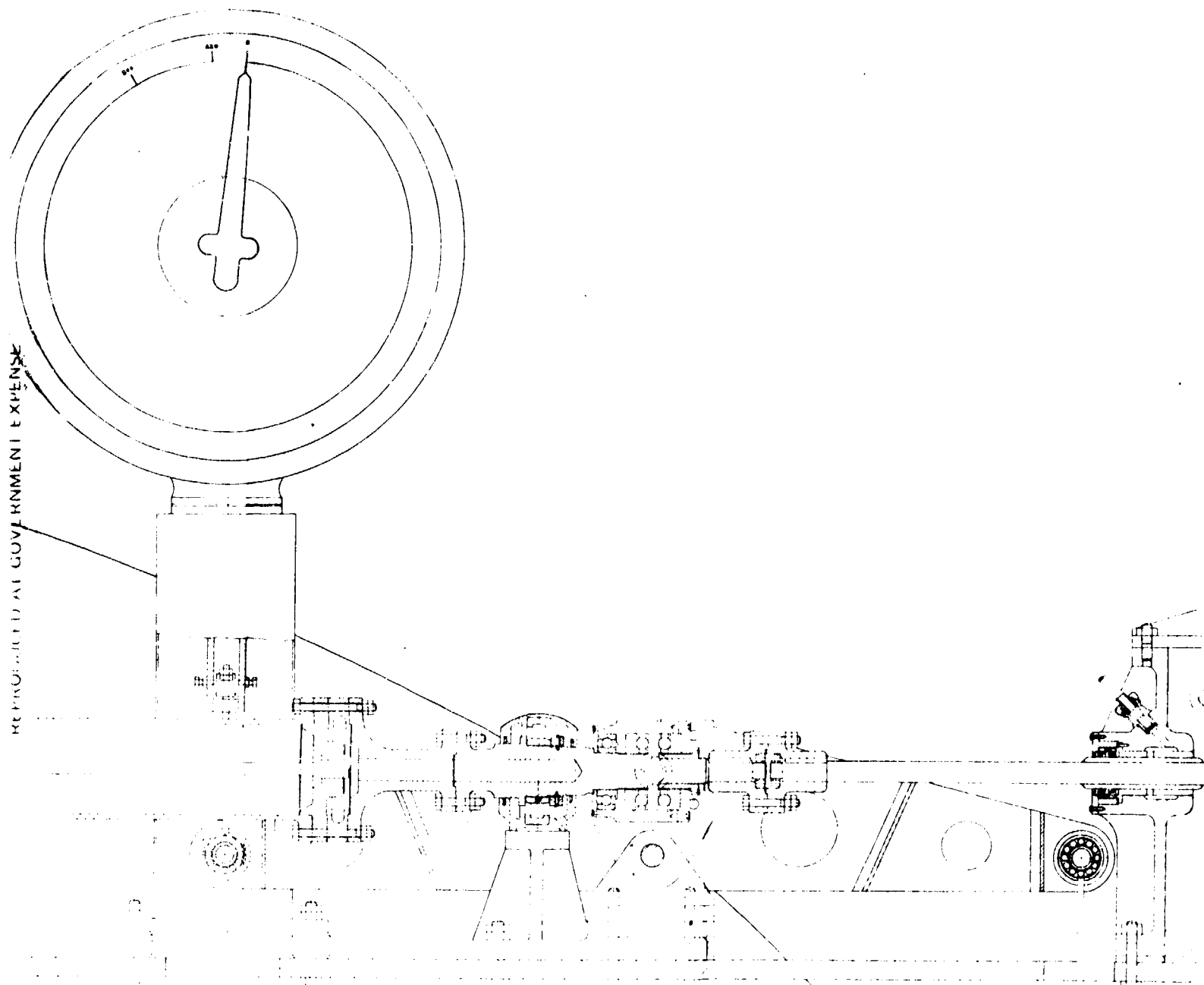
No actual propeller cavitation tests had been performed with propellers operating behind a complete ship model shape because the tunnel instruments had been damaged by fire from

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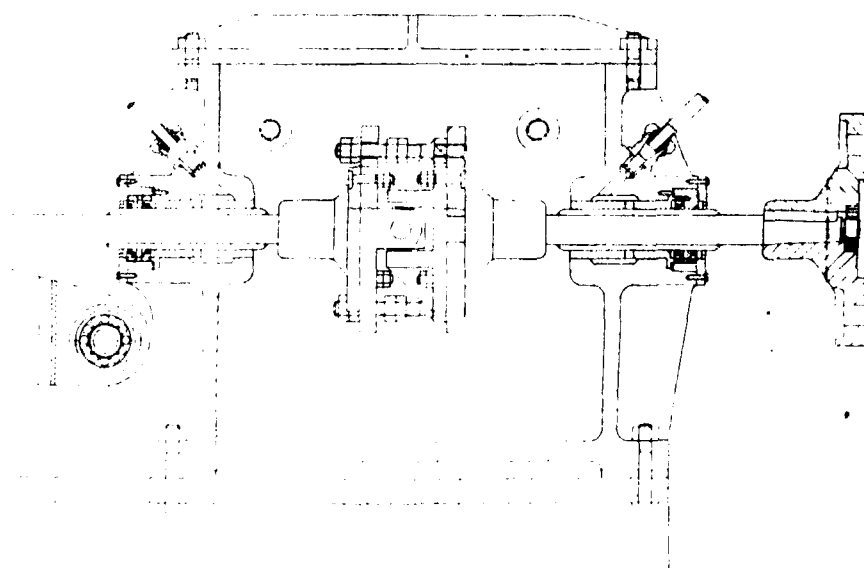


FIGURE 37

CAVITATION TUNNEL II

PROPELLER DYNAMOMETER
APPARATUS

RESTRICTED.

Cavitation Tunnel II at Hamburgische
Schiffbau Versuchsanstalt, Cont'd.

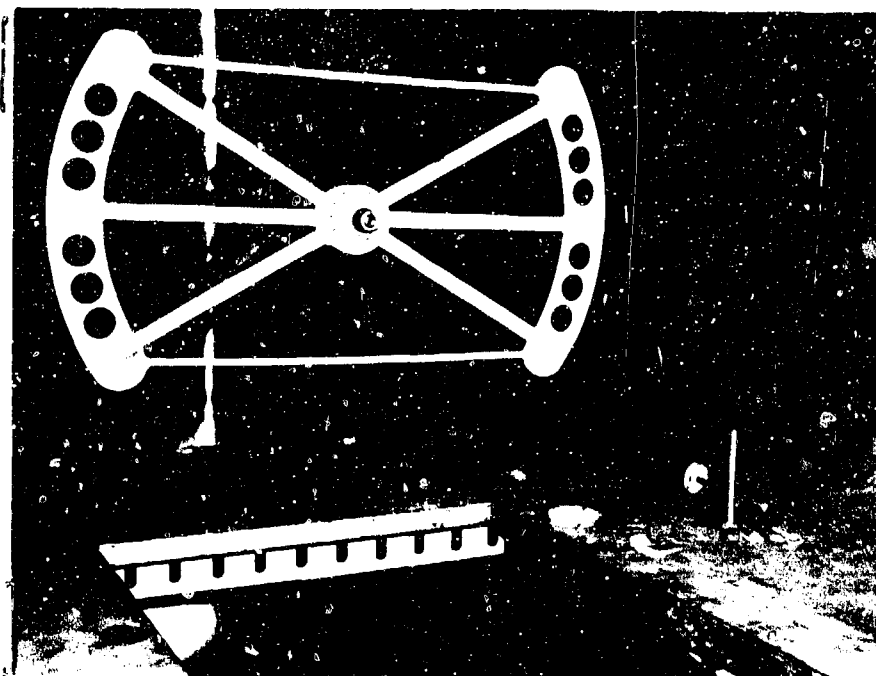


Fig. 38

H.S.V.A. CAVITATION TUNNEL II, JUNE 1945.

An interior view of the test section shows the apparatus for calibrating the torsion rod. On the bottom of the test section on the right side may be seen the pitot tube for measuring the water velocity.

RESTRICTED.

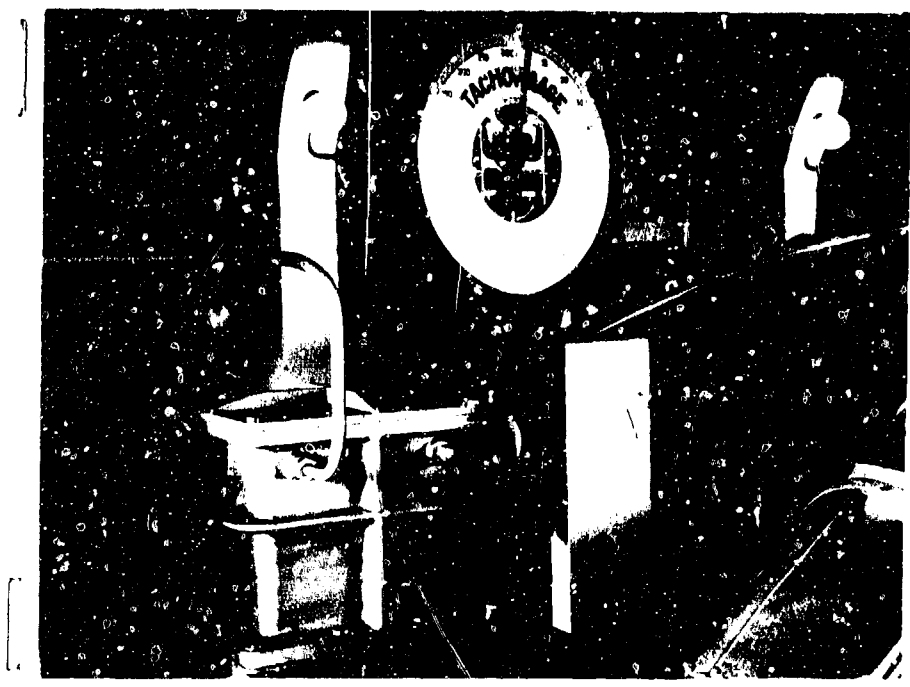


Fig. 39.

H.S.V.A. CAVITATION TUNNEL II, JUNE 1945.

DYNAMOMETER INSTALLATION.

RESTRICTED.

Cavitation Tunnel II at Hamburgische
Schiffbau Versuchsanstalt, Cont'd.

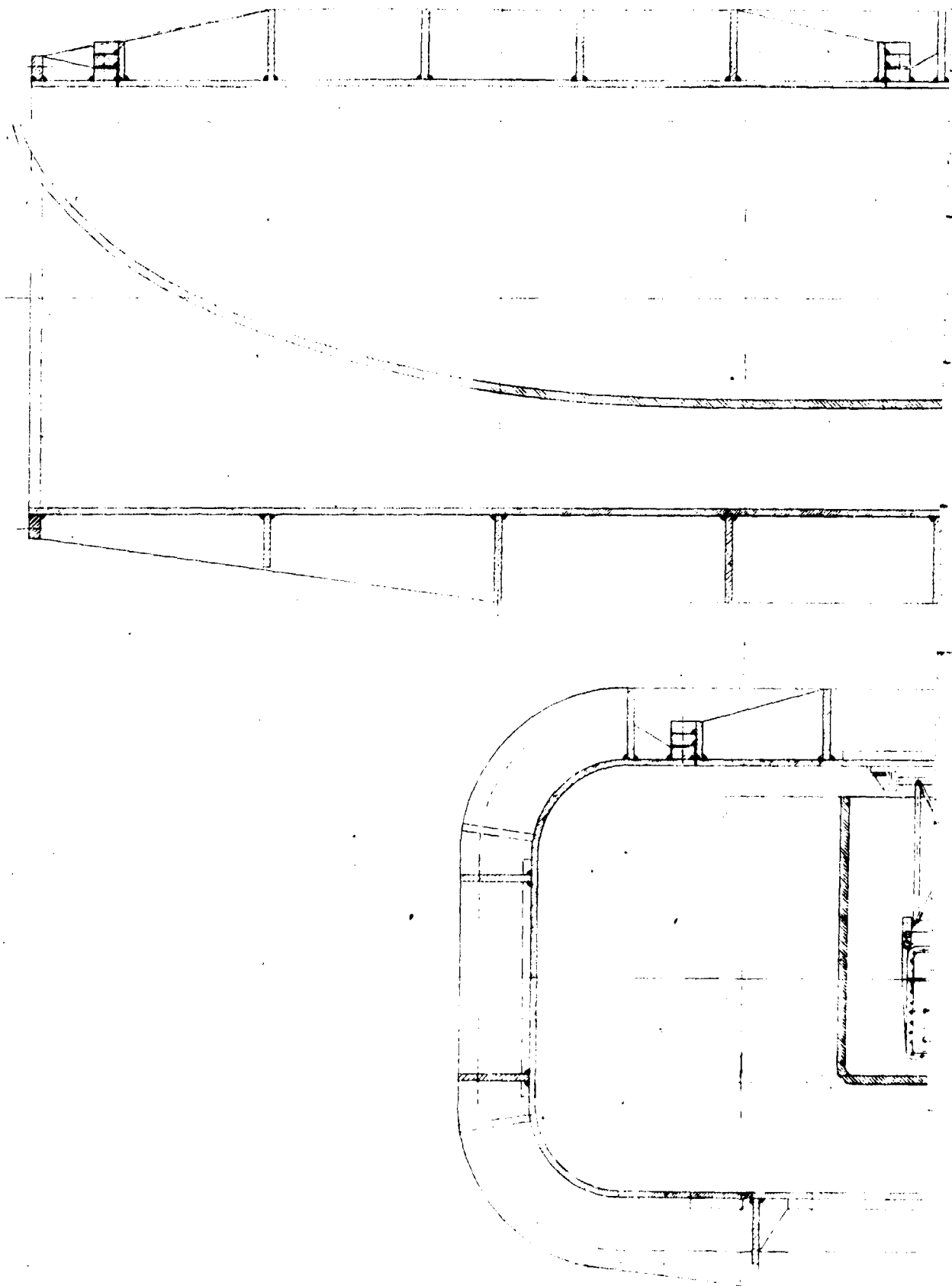
incendiary bombs in August, 1943 and repairs were not quite completed when the war ended. However, a preliminary design of an arrangement for testing models with one to five screws was completed in 1943. Fig. 40 shows a ship model form mounted in the test section. The dynamometer inner shaft is connected to a watertight aluminum gear casing freely suspended from the top of the test section inside the model. The casing houses the gear arrangement for driving the individual model shafts. The total thrust and torque can be measured directly with the propeller dynamometer thrust and torque measuring instruments. It was intended ultimately to devise a method for measuring the thrust of the individual shafts by using small pressure capsules. The water speed was to be determined by a speed calibration with equality of thrust for the cavitation test and the basin propulsion test.

Difficulties could be expected in obtaining constant and sufficiently small friction forces for accurate measurements. Also, in view of the size of the model compared to the test section, the lines of flow and wake distribution at the propeller could be considered only approximate. Nevertheless, the method appears feasible as a first approach to a difficult problem.

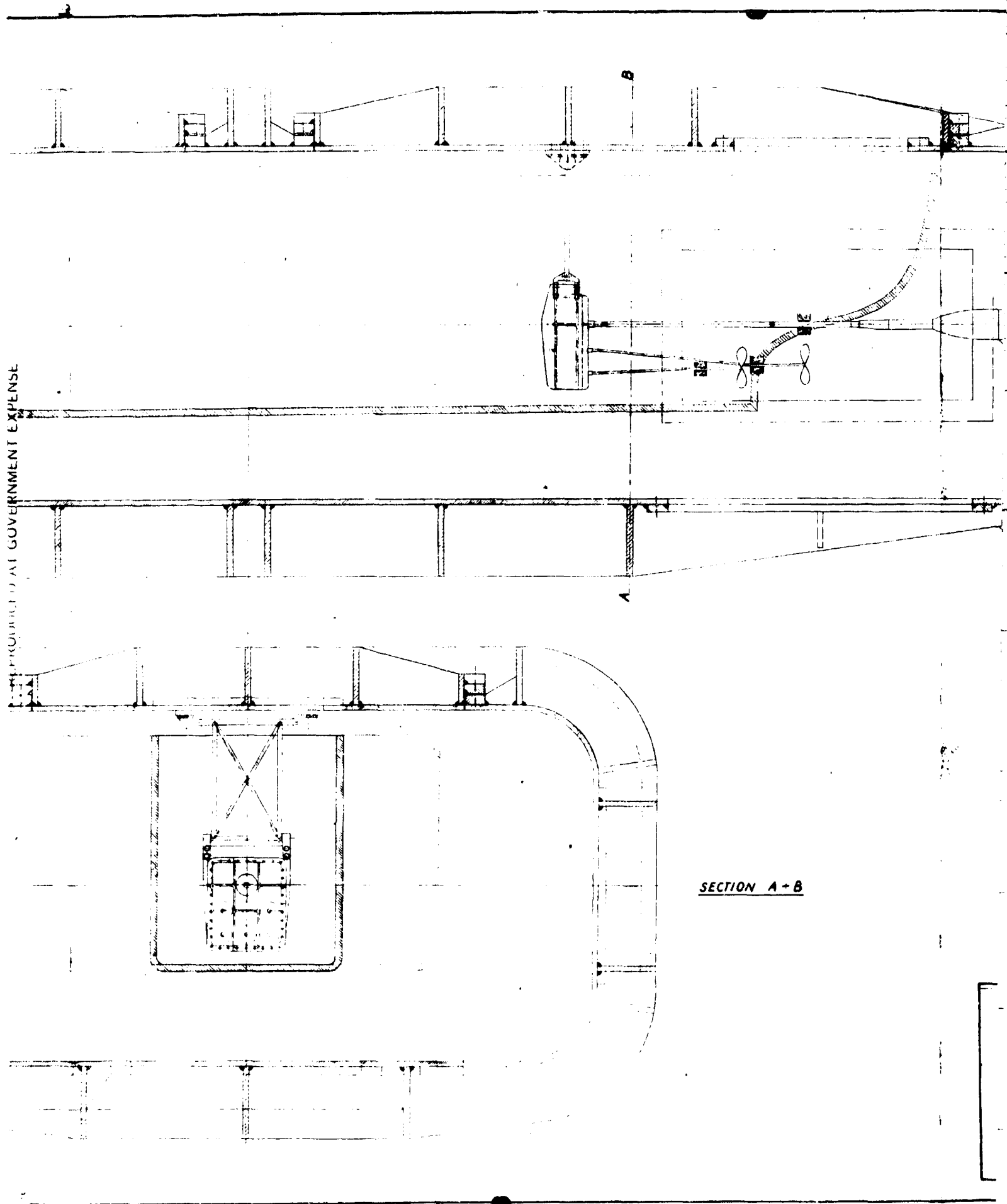
3. Test Apparatus for Contra-Rotating Propellers.

An arrangement for testing contra-rotating torpedo propellers in the large cavitation tunnel was designed by H. S. V. A. in 1943 and was under construction at Germania Werke, Kiel at the end of the war. Fig. 41 shows the measuring apparatus built in a watertight casing in the form of a torpedo tail section. The drive shaft of the propeller dynamometer drives a differential bevel gear train in the extreme tail section so that the forward propeller turns in the same direction as the drive shaft and the after propeller turns in the opposite direction. The total thrust and torque can be measured with the conventional thrustmeter and torsionmeter of the propeller

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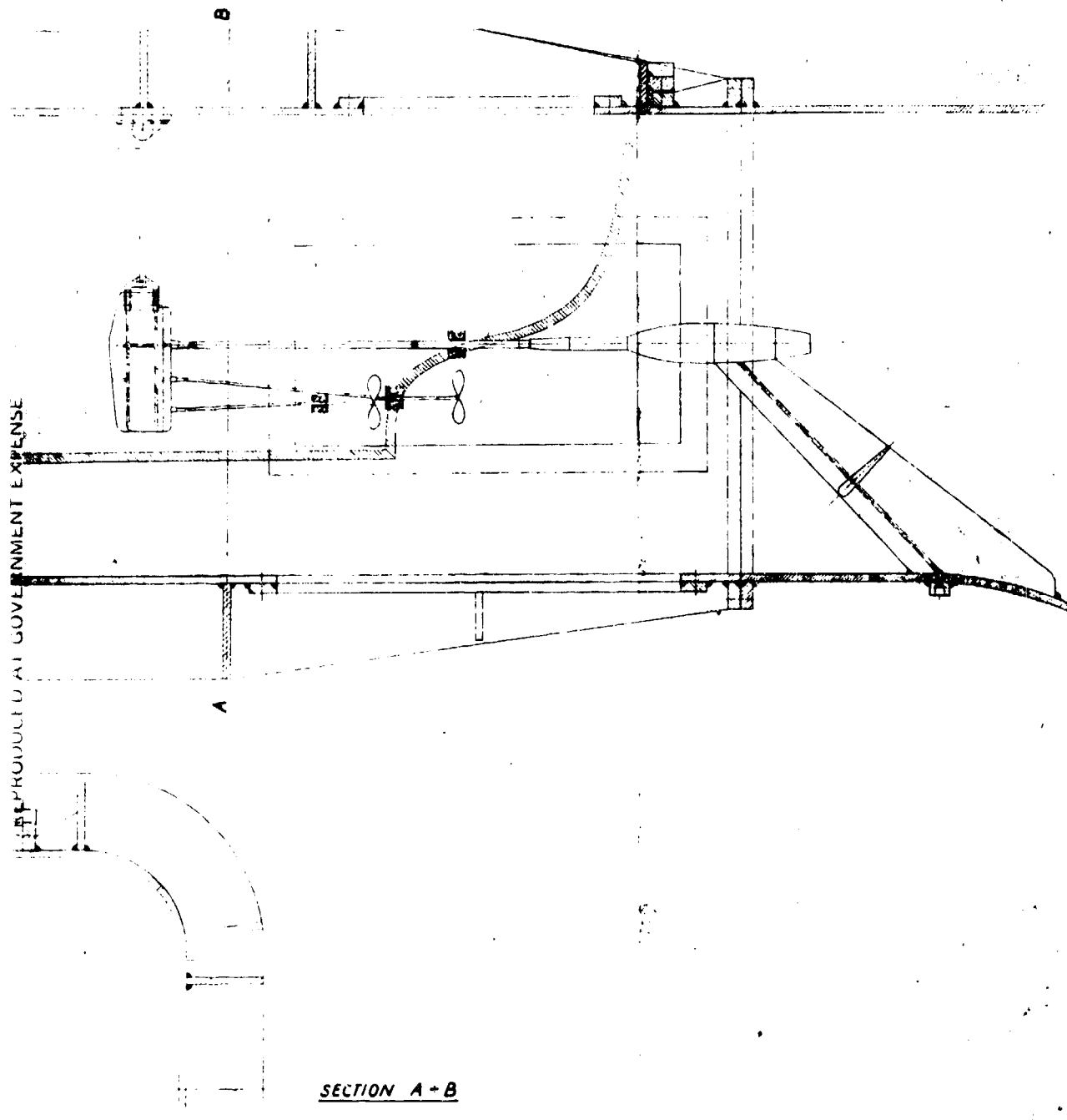


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SECTION A+B

PRODUCED AT GOVERNMENT EXPENSE

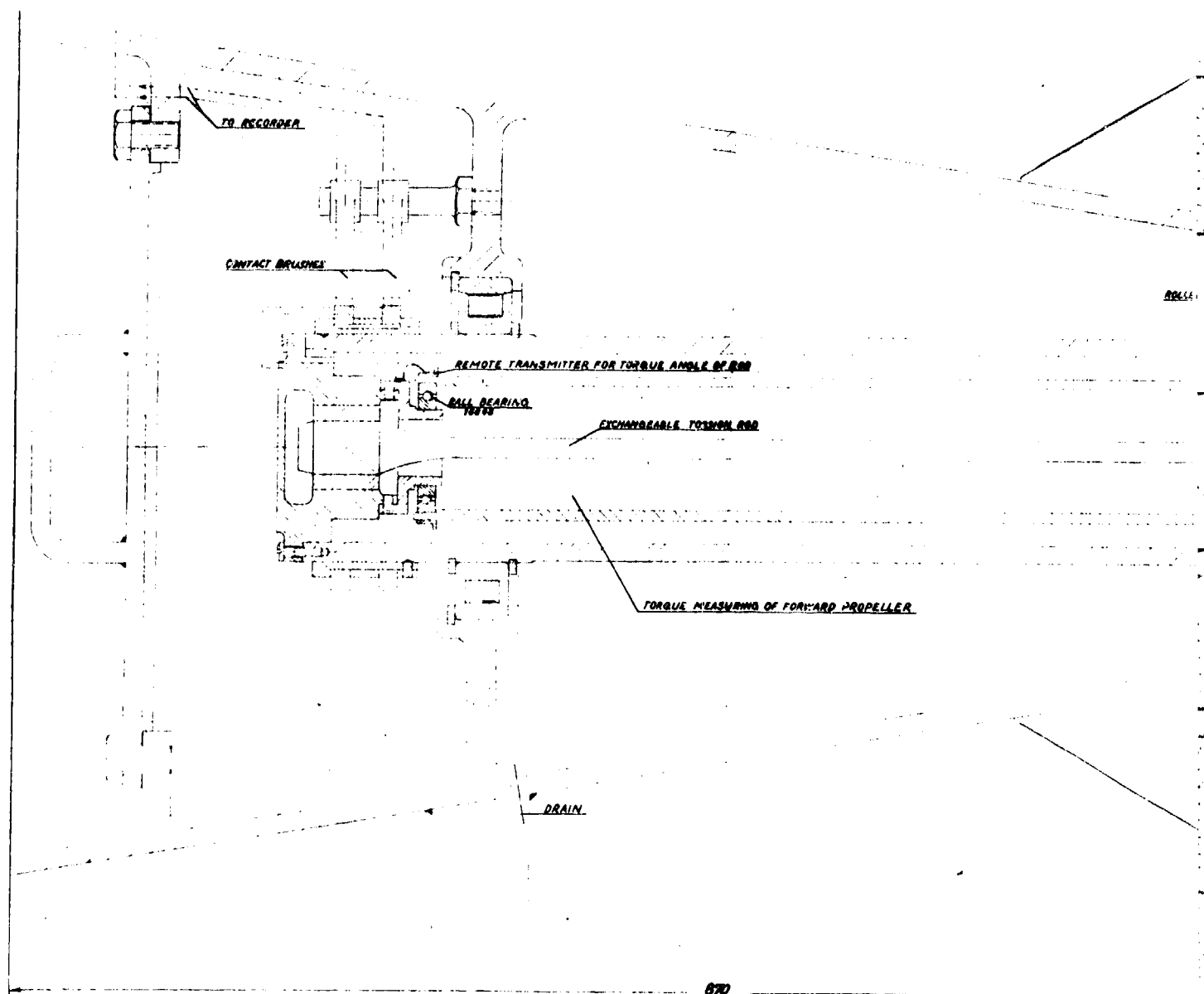


SECTION A-B

FIG. 40
ARRANGEMENT FOR TESTING MULTIPLE
SCREW SHIP MODEL FORMS

H.S.V.A. CAVITATION TUNNEL II

REPRODUCED AT GOVERNMENT EXPENSE



REPRODUCED AT GOVERNMENT EXPENSE

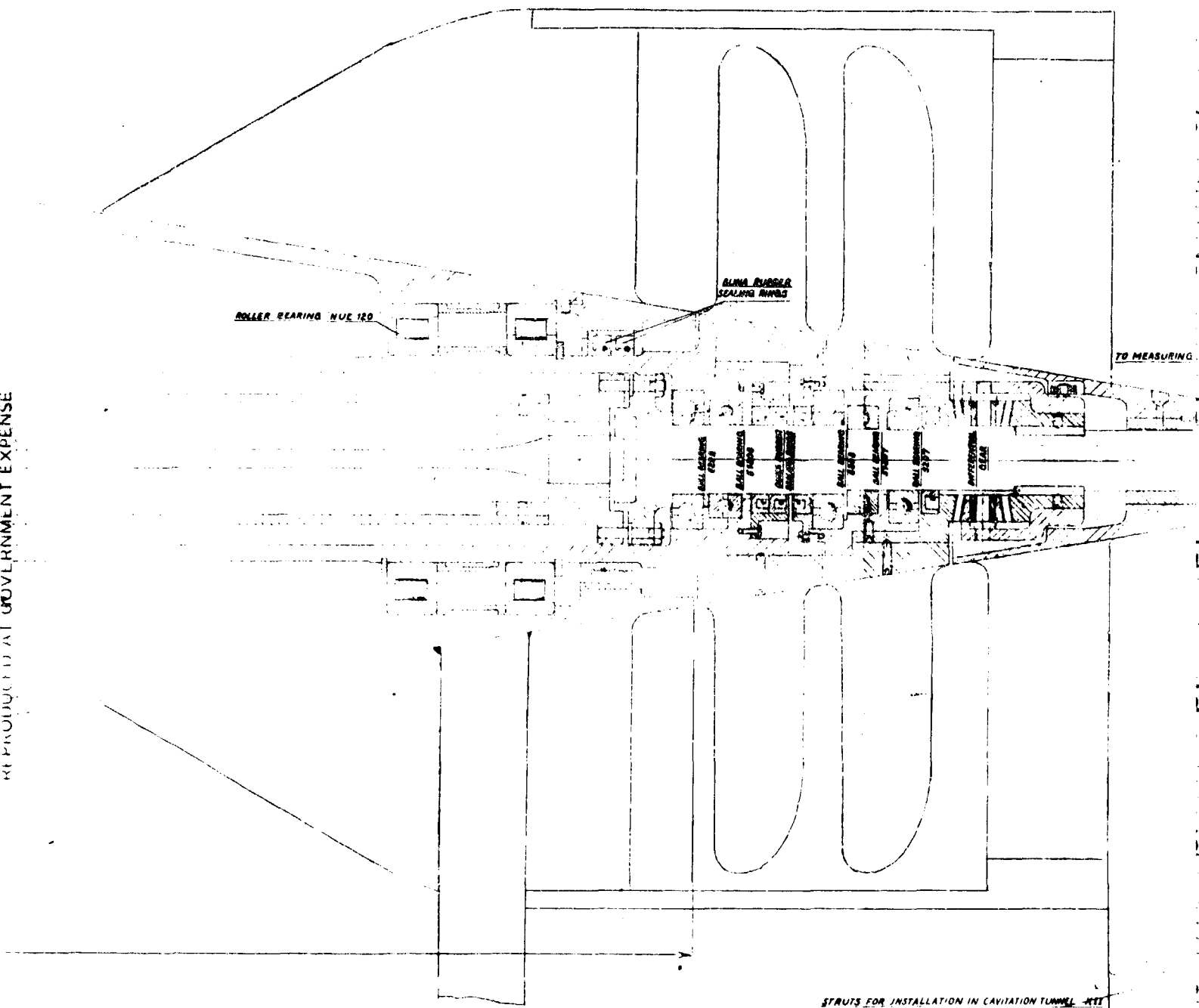


FIGURE 41

DRIVING ARRANGEMENT AND MEASURING
APPARATUS FOR CONTRA-ROTATING
TORPEDO PROPELLERS

H.S.V.A. CAVITATION TUNNEL

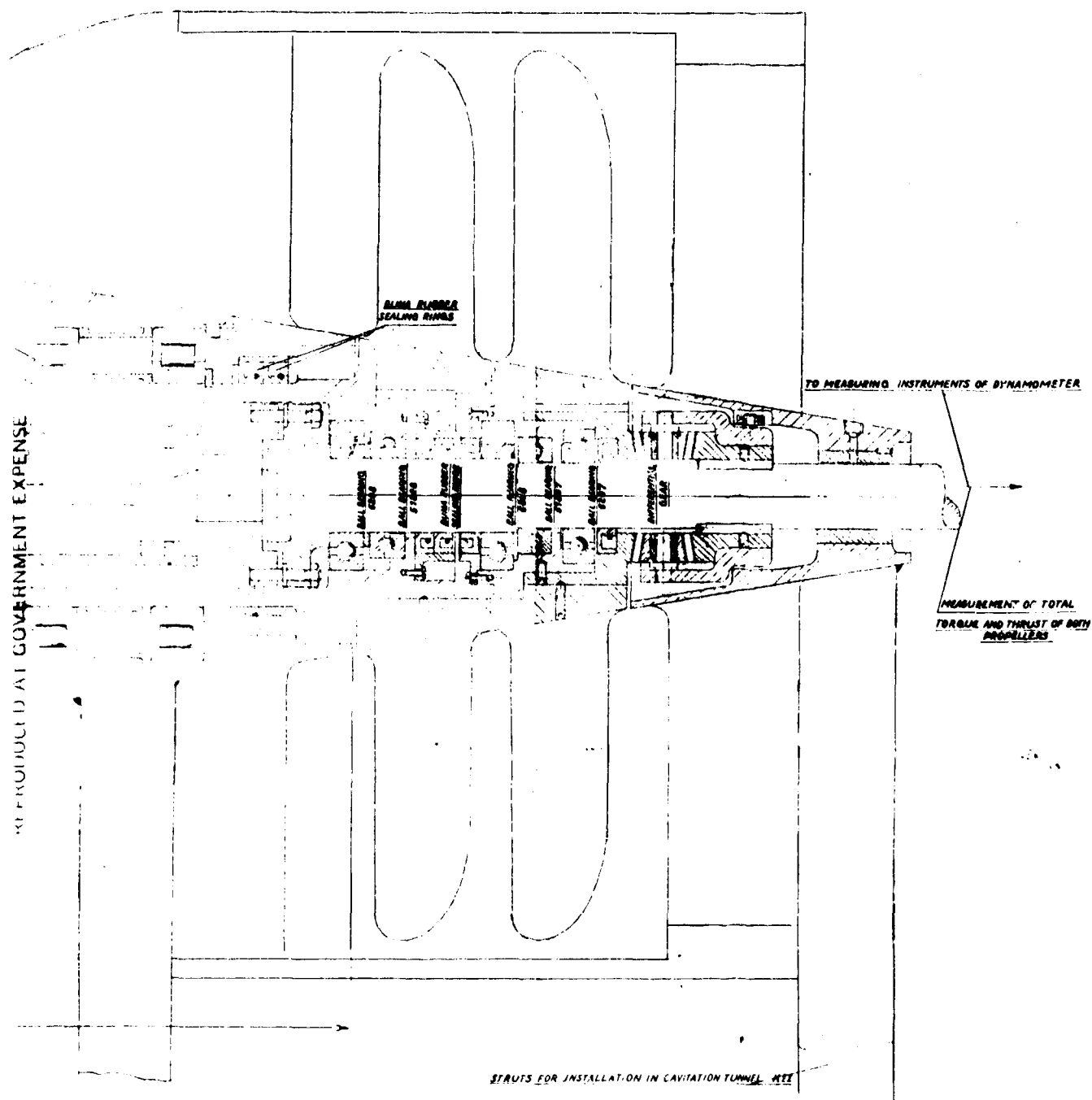


FIGURE 41

DRIVING ARRANGEMENT AND MEASURING
APPARATUS FOR CONTRA-ROTATING
TORPEDO PROPELLERS

HSVA CAVITATION TUNNEL II

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RESTRICTED.

Cavitation Tunnel II at Hamburgische
Schiffbau Versuchsanstalt, Cont'd.

dynamometer. The torque of the forward propeller can be measured by an additional calibrated torsion rod and potentiometer in the inner housing of the apparatus. Ball bearings are used throughout the mechanism to reduce the friction forces and Buna rubber spring seals are used to prevent ingress of water at the propellers and the drive shaft.

This contra-rotating propeller test arrangement is advantageous in that the propellers are operating in an approximately correct wake field so that the load distribution over the propeller radius approximates the actual operating condition.

IV Cavitation Tunnel at Nederlandsche Scheeps-
bouwkundig Proefstation, Wageningen.

A. Description of Installation.

The cavitation tunnel at Wageningen, shown in Fig. 42 was constructed in 1939 and has been described fully in publications (6, 7). For convenience, the principal characteristics will be listed, together with supplemental unpublished information.

The tunnel was designed primarily by personnel of the Hamburg basin in 1938. The design of the lower section, including the elbow before the propeller pump, was based on results of wind tunnel tests at the Netherlands Technical College in Delft. Unlike the two cavitation tunnels at Hamburg, which are of all-welded construction of shipbuilding steel, the Wageningen tunnel is constructed principally of cast steel except for the two vertical connecting sections, the heating jacket section, and the honeycomb section, which are of welded steel plate construction. The tunnel structure was fabricated by N.V. Werkspoor in Amsterdam, the instruments

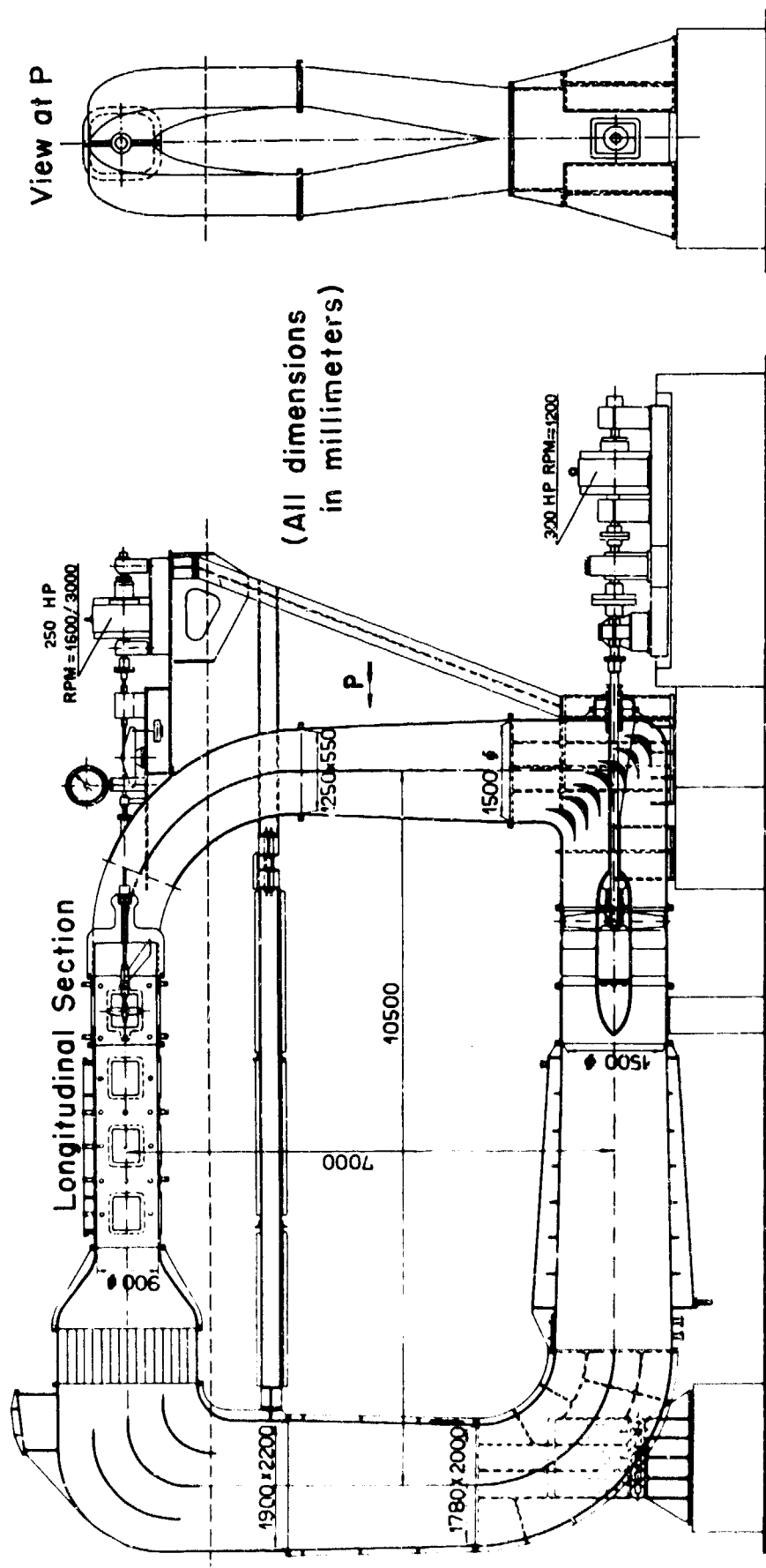
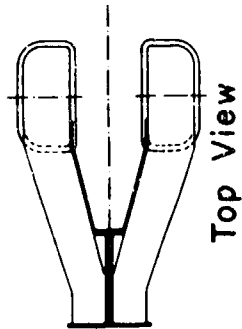


Fig. 42
WASINGEN CAVITATION TUNNEL

RESTRICTED.

Cavitation Tunnel at Nederlandsche Scheepsbouwkundig
Proefstation, Wageningen.

were designed and furnished by H.S.V.A., and the electrical equipment was furnished by N.V. Electrotechnische Industrie in Slikkerveer.

The principal characteristics of the tunnel are:

Test section

Height 0.9 m. (35.4 in.)
Width 0.9 m. (35.4 in.)
Cross-section area 0.77 m² (1192 in.²)
Length 5.0 m. (16.4 ft.)
Velocity 10 m/sec (19.45 knots)

Alternate test section

Height 0.65 m (25.6 in.)
Width 1.30 m (51.2 in.)

Vertical height between upper and lower legs 7m.
(23.0 ft.)

Driving motor

Horsepower 300
RPM 1200

Propeller pump RPM 300

Model propeller dynamometer

Horsepower 250
RPM (max) 2500
Thrust (max) 1250 kg. (2756 lbs.)

Maximum model propeller diameter 0.5 m. (18.19 in.)

The measuring instruments for torque and thrust, the water speed pitot tube arrangement, the static pressure measurement, the grease sealing method, and the compensating chamber for eliminating the thrust correction due to the pressure difference between the tunnel test section and the

RESTRICTED.

Cavitation Tunnel at Nederlandsche Scheepsbouwkundig
Proefstation, Wageningen, Cont'd.

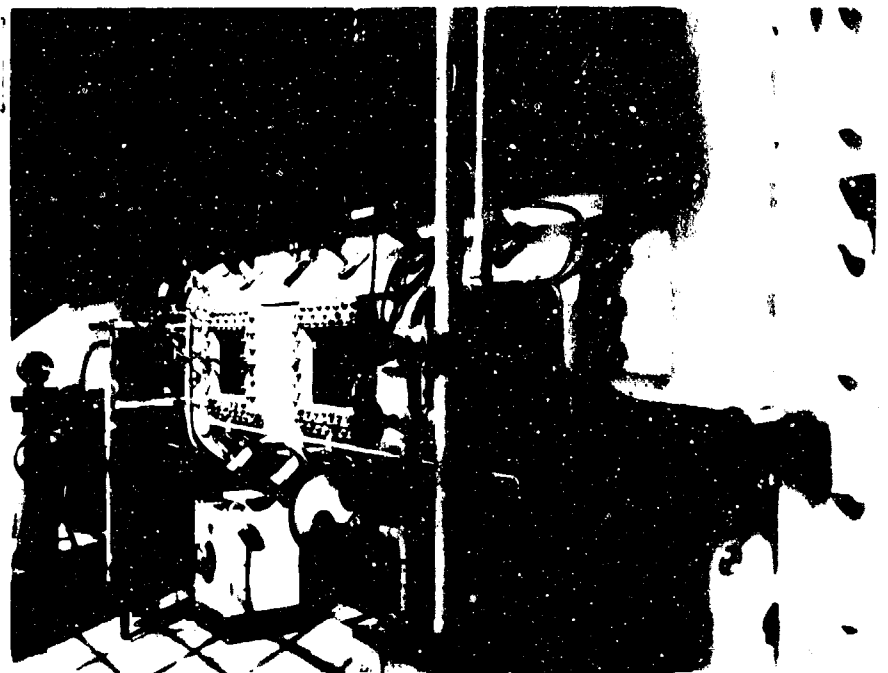


Fig. 43

WAGENINGEN CAVITATION TUNNEL, JULY 1945.
Test Section and Operating Station.

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Cavitation Tunnel at Nederlandsche Scheepsbouwkundig
Proefstation, Wageningen, Cont'd.



Fig. 44.

WAGENINGEN CAVITATION TUNNEL, JULY 1945.

A view of the upper level of the tunnel shows the nozzle, test section, and the three-component dynamometer installed above the test section.

RESTRICTED.

Cavitation Tunnel at Nederlandsche Scheepsbouwkundig
Proefstation, Wageningen, Cont'd.

large cavitation tunnel. Such work was contemplated, but test arrangements have not yet been designed.

An alternate rectangular test section, 1.30 meters wide 0.65 meters high, and a suitable nozzle (Fig. 45) can be installed in the tunnel for testing hydrofoils. Up to the present time, the rectangular test section has never been installed. A horizontal truss of adjustable length can be used to force the vertical tunnel sections apart for installing the alternate sections, as well as to provide additional strength.

When the German army evacuated from the Wageningen area about April 1945, all of the tunnel instruments were damaged or destroyed and the main driving motor and the power supply motor-generator were removed. Fig. 46 and 47 show the condition of the tunnel in July 1945.

B. Projects and Research.

During World War II little work was accomplished in the Wageningen tunnel except for the German firm Sachsenberg, designers of the hydrofoil speed boats VS-8 and VS-10. A large number of VS-8 and VS-10 wide blade, high speed propellers with pitch ratios up to 2.0 were tested for cavitation characteristics. The methods of testing followed those used by Lerbs. Most characterization tests were conducted with a constant water speed of 5.5 or 6.0 meters per second. Dr. van Lammeren noted that at the low values of the speed coefficient,

$\frac{v}{a}$, the thrust coefficient curves for different values and of the cavitation number tended to converge at one value. This could probably be explained by the fact that complete suctionside cavitation occurred for all the range of cavitation numbers tested at the low speed coefficients.

RESTRICTED.

Cavitation Tunnel at Nederlandsche Scheepsbouwkundig
Proefstation, Wageningen, Cont'd.

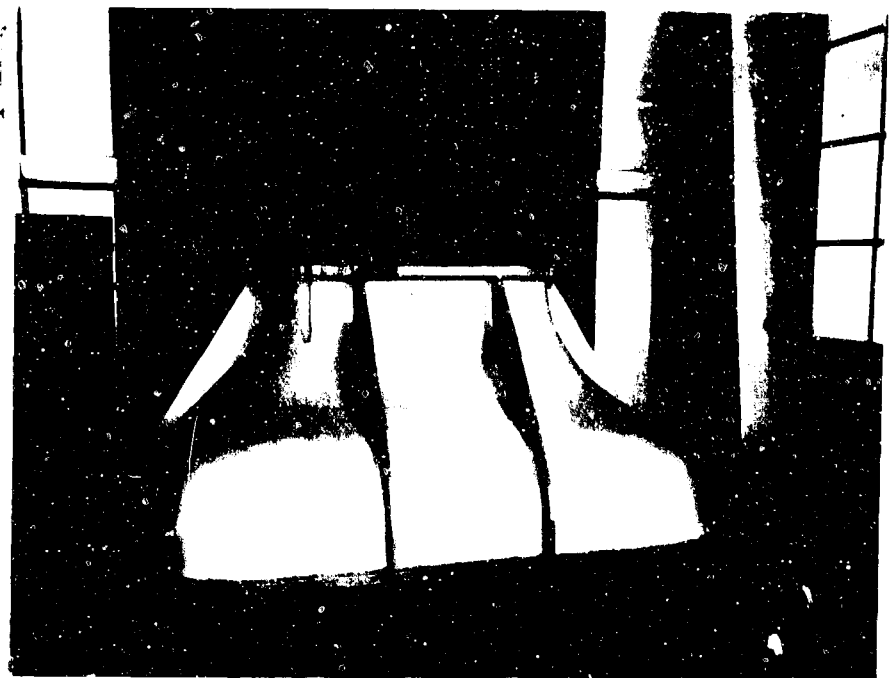


Fig. 45.

WAGENINGEN CAVITATION TUNNEL ALTERNATE NOZZLE.

The alternate nozzle, 1.30m. wide and 0.65 high at the exit, is intended for testing hydrofoils in the tunnel.

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Cavitation Tunnel at Nederlandsche Scheepsbouwkundig
Proefstation, Wageningen, Cont'd.



Fig. 46

WAGENINGEN CAVITATION TUNNEL UPPER LEVEL, JULY 1945.

All of the measuring instruments are damaged or destroyed.

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Cavitation Tunnel at Nederlandsche Scheepsbouwkundig
Proefstation, Wageningen, Cont'd.

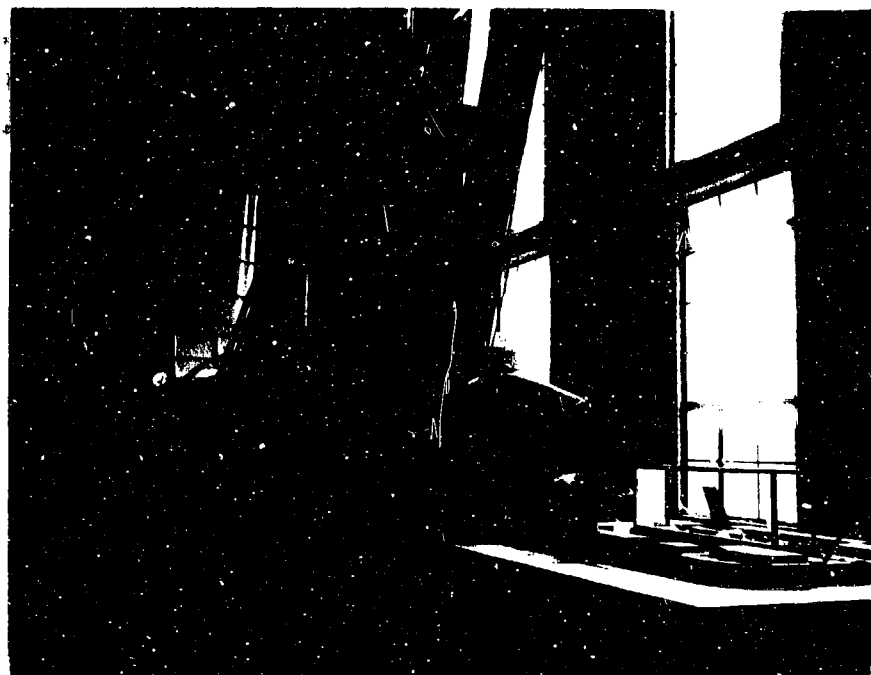


Fig. 47

WAGENINGEN CAVITATION TUNNEL LOWER LEVEL, JULY 1945.

The main propeller driving motor was removed by the German Army.

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Cavitation Tunnel at Nederlandsche Scheepsbouwkundig
Proefstation, Wageningen, Cont'd.

In order to test the lifting hydrofoils used in the Sachsenberg hydrofoil boats, a large three-component dynamometer was constructed on the top of the tunnel test section. (Fig. 44). The installation was not completed at the end of the war in Europe and no hydrofoil tests had been performed. The measuring elements intended to be used for measuring the component forces were the centrifugal type dynamometers developed at Wageningen. Fig. 48 shows schematically the method of measuring a force with the centrifugal dynamometer. If the force is greater than the reaction of the dynamometer, the circuit to the small series motor closes, the dynamometer accelerates, and the weights move outward by centrifugal force. By the pivot arm arrangement of the dynamometer, the shaft to which the force is applied moves inward to reopen the contact to the motor circuit so that the motor slows down and the cycle is repeated. An electric contactor on the motor shaft records the motor RPM as a measure of the force component. Forces as great as 25 kg. (55 lbs.) can be measured with a 1/16 H.P. motor.

As a result of the overall propeller cavitation experiences at Wageningen, a formula has been devised for the minimum projected area of ship screws without loss in efficiency

from cavitation: $T/A_p = 1.955 (p_o - p_v)^{0.733} v_a^{0.535}$

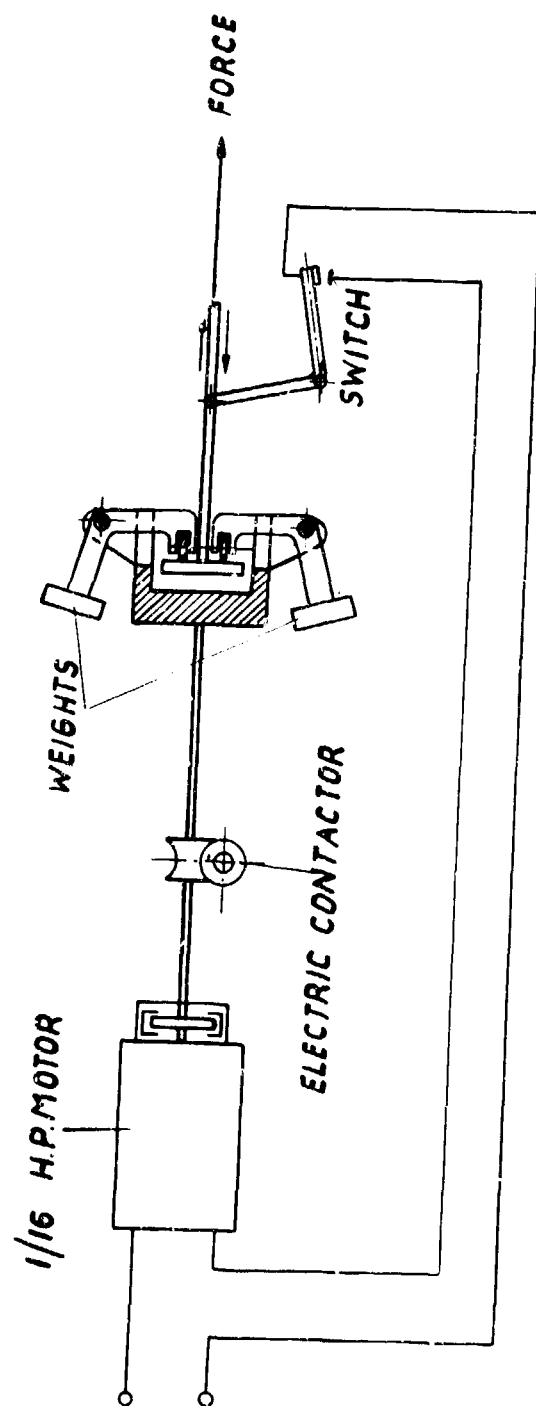
where T = thrust in kg.

A_p = total blade projected area in m^2

p_o = static pressure at propeller center in
 kg/m^2

p_v = vapor pressure in kg/m^2

v_a = speed of advance in m/sec.



WAGENINGEN CENTRIFUGAL
DYNAMOMETER
SCHEMATIC DIAGRAM

FIGURE 48

RESTRICTED.

V. The Cavitation Tunnel at the Kaiser Wilhelm Institute, Göttingen.

A. History of Development.

A small cavitation tunnel for general research had been constructed at Göttingen in 1927. With the advent of World War II, problems of high speed flow in connection with the movement of projectiles in water, determination of constant pressure surfaces, and the air-water entry problem arose. In order to investigate these problems, it became necessary to design an installation in which cavitation numbers as low as 0.01 could be attained. Dr. Reichardt, working under Prof. Prandtl, made an analysis of the technical problems involved in such an installation. In order to avoid the necessity of constructing a powerful installation to obtain low cavitation numbers by increasing the stagnation pressure q_0 , Dr. Reichardt supervised the complete redesign of the original cavitation tunnel to a "free-jet" arrangement, with the result that very low cavitation numbers could be attained by reducing the static pressure p_0 . The free jet tunnel was constructed in 1942 and has been in operation for slightly over two years.

The following description of the original installation, the technical problems involved in the design of very low cavitation numbers, and the description of the final tunnel design were obtained from conversations with Dr. Reichardt and from a condensation of a recent report of the Kaiser Wilhelm Institute (8).

B. The Original Göttingen Cavitation Tunnel.

The old cavitation installation shown in Fig. 49 was in the form of a closed circular channel employing a centrifugal pump to circulate the water from a large vertical chamber of 1.7 square meters cross sectional area, through the nozzle, test section, diffuser, elbow, return duct, pump, and back to the vertical chamber. A vacuum pump was connected above the free water surface in the vertical chamber. The static pressure p_0 depended on the air pressure above the water surface, the height of water in the chamber, and the

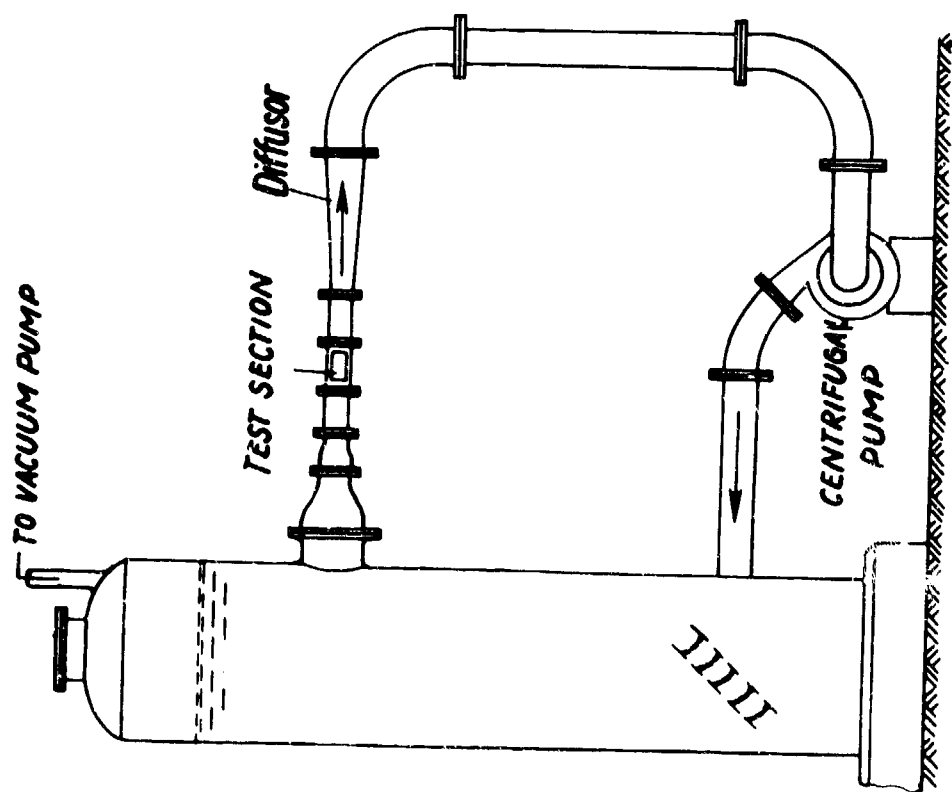


FIG. 49

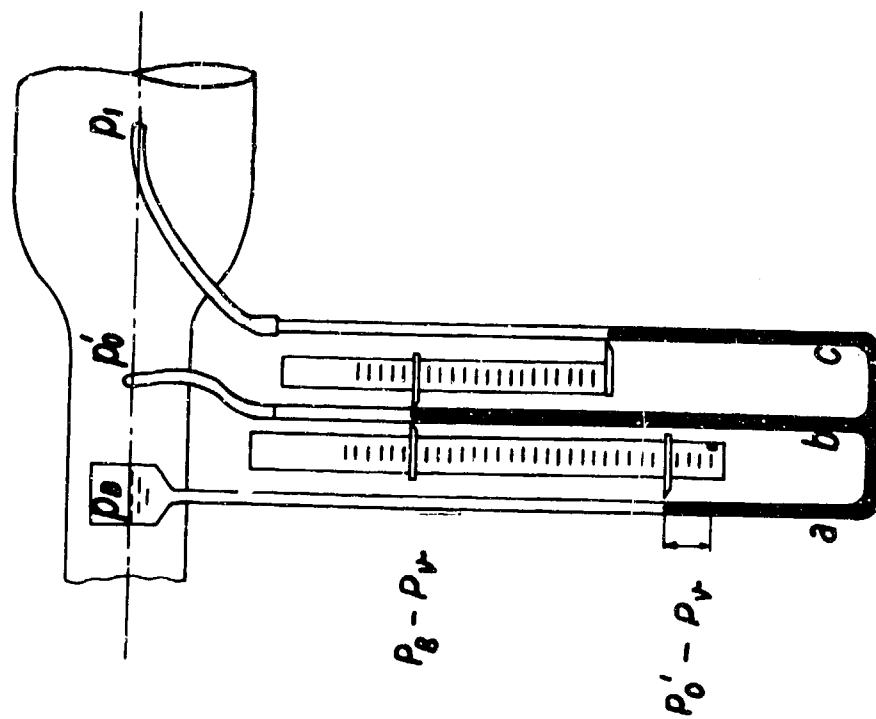


FIG. 50

ORIGINAL GÖTTINGEN CAVITATION TUNNEL

RESTRICTED.

The Cavitation Tunnel at the Kaiser Wilhelm
Institute, Göttingen. Cont'd.

momentary pressure drop through the nozzle as well as the minor effects of model displacement and cavitation bubbles on the model and in the test section. Since static pressure of the undisturbed flow, p_o , cannot be measured directly in a closed channel, the approximate pressure p_o' was measured in the vicinity of the model and a correction applied. That is,

$p_o = p_o' - kq_o$ where k is a factor which depends primarily

on the displacement effect of the model. The static pressure tap for p_o' was made in the test section just ahead of the model, and the pressure tap p_1 in the nozzle antechamber. To indicate pressure differentials, the mercury gage shown in Fig. 50 was connected to the pressure points through water-filled tubes. Leg a was connected to the level chamber whose water surface coincided with the vertical center of the test section, leg b to the tap p_o' , and leg c to tap p_1 . The water surface of the level chamber was open to atmospheric pressure p_B . Between a and b the pressure differential $p_B - p_o'$, and between b and c the pressure differential $p_1 - p_o'$, proportional to the stagnation pressure, were indicated. The vapor pressure for the applicable temperature, determined from steam tables, was used in calculating the cavitation number. In order to establish a given cavitation number, five values were necessary, including the four measurements $p_B - p_o'$, $p_B - p_1$, $p_1 - p_o'$, water temperature, and the channel correction factor k . A later simplification was made by using a scale with movable pointers between gauge legs a and b, as shown in Fig. 50. The upper pointer was set to the scale value $(p_B - p_v)$. By moving the scale, the pointer was brought into agreement with the mercury level b. If the lower pointer was then adjusted to the mercury level of leg a without moving the scale, the value $(p_1 - p_v) - (p_B - p_o')$ $= p_o' - p_v - q_o$ could be read directly.

The original tunnel installation was satisfactory with values of > 0.1 but accurate measurements at lower values were not possible.

RESTRICTED.

The Cavitation Tunnel at the Kaiser Wilhelm
Institute, Göttingen. Cont'd.

The corresponding distance h from the model to the top of the test section is only $h = \frac{21.2 \times 12}{62.4} = 4.08$ inches.

Therefore, it can be seen that a very small test section and consequently very small models would have to be employed to obtain very low cavitation numbers with a closed channel.

With the test section arranged as a free jet, Fig. 51, the same static pressure exists on all sides, but the acceleration of the fluid particles due to gravity produces some curvature of the streamlines. With a horizontal jet, the streamlines are essentially parallel, but with a vertical jet, the streamlines are divergent. The influence of the bending or divergence becomes smaller as the stagnation pressure increases. While very low and constant cavitation numbers can be obtained with a free jet, small models must also be specified if the influence of the curvature of the streamlines is to be kept negligible at moderate stagnation pressure.

3. Method of Measuring the Static Pressure p_0

In a closed jet installation, the static pressure is normally obtained from a tap in the test section. Even a very slight burr at the pressure tap introduces errors in the static pressure measurement which become increasingly important at low cavitation numbers. Also since water pressure is measured, water must also be used as the medium of pressure transfer in the connecting lines to the manometer. Unless the manometer is installed well below the test section and the connecting lines to the pressure tap are very straight so that the pressure in the lines is always greater than in the test section, erroneous readings may occur due to the separation of vapor or dissolved air in the connecting lines at very low cavitation numbers. The possibility of this error can be avoided with certainty if vapor or gas is used for transmitting the pressure p_0 , in which case a leveling chamber such as shown in Fig. 52 can be used to afford a transition from the gas to the fluid phase.

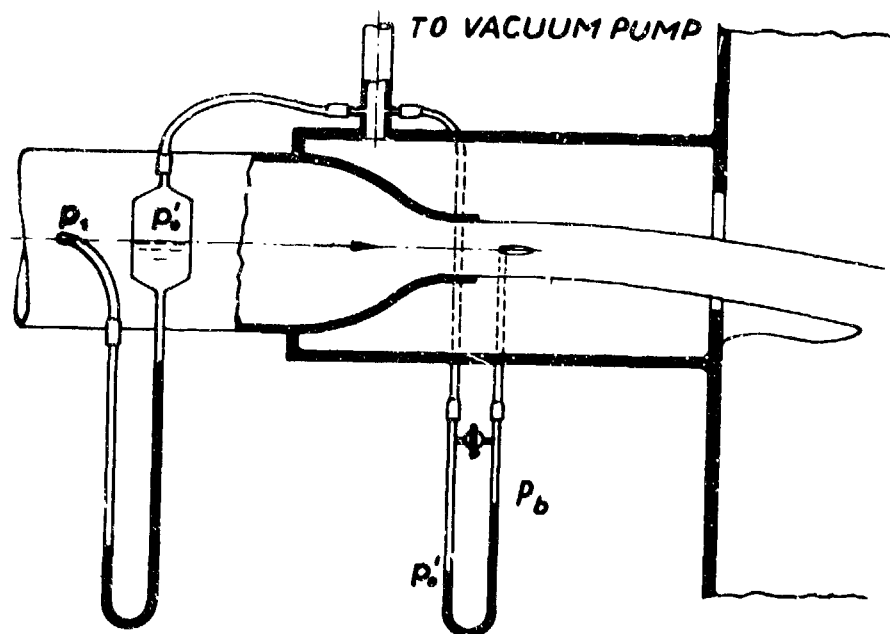


FIG.51

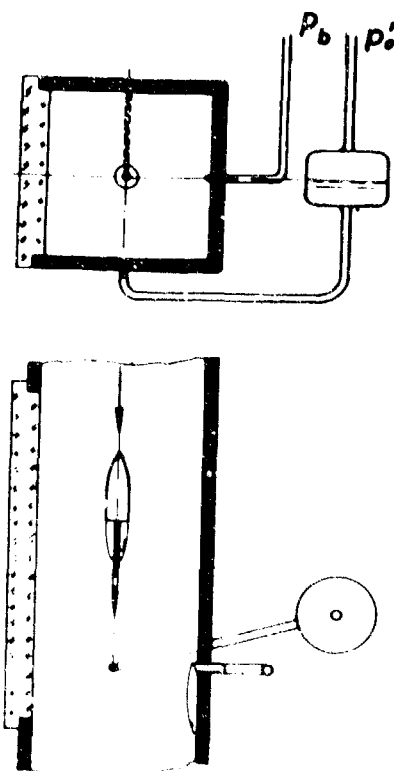


FIG.52

RESTRICTED.

The Cavitation Tunnel at the Kaiser Wilhelm
Institute, Göttingen. Cont'd.

With a free jet, the pressure p_o' can be measured directly from the vapor or gas surrounding the jet, without the possible source of error arising from any slight burr at the pressure tap or without the necessity of using a leveling chamber.

4. Method of Measuring the Bubble Pressure p_b

With the previous installation at Göttingen and at other institutions, the vapor pressure, p_v , has been used to calculate the cavitation number. At very low cavitation numbers the dependence of the vapor pressure on temperature makes possible large percentage errors of the cavitation number with small temperature changes. Also the actual bubble pressure, p_b , is normally greater than the vapor pressure, p_v , due to dissolved air in the water.

An ingenious, though extremely simple method has been proposed and adopted by Dr. Reichardt to measure the actual bubble pressure and use that value in the cavitation number in place of the vapor pressure. A diagonally-cut tube projecting slightly through the wall of the test section with the sharp edge to the stream creates a cavitation bubble on the wall. The pressure in the bubble can be transmitted directly through the tube to a manometer. With a free jet installation, the static pressure p_o' can be measured directly against the bubble pressure p_b (see Fig. 51), so that the manometer reads $p_o' - p_b$, which is the numerator in the cavitation number after the channel correction is applied.

The latter method can also be applied to open jet tunnels, such as those at the David Taylor Model Basin and Massachusetts Institute of Technology, by creating an artificial bubble on a small faired plate or body in the stream at the test section and measuring the difference in pressure between the free surface and the bubble. An additional hydrostatic pressure correction would have to be applied for the head of water over the model in the test section to obtain the numerator of the cavitation number.

RESTRICTED.

The Cavitation Tunnel at the Kaiser Wilhelm
Institute, Gottingen, Cont'd.

into the diffuser. In an actual test, alternating disturbance pressures produced rhythmic fluctuations in the flow through the test section after cavitation advanced well into the expansion chamber. The arrangement whereby the pressure in the test section is held constant was not tested in that it was considered unfavorable from the point of view of stability with cavitation.

As a study in determining means of converting the stream kinetic energy into potential energy in a free jet installation, the scheme shown in Fig. 53 was considered. With the vertical jet or fountain arrangement, the stream, with little remaining kinetic energy, is caught in a horizontal chamber from where it is led down to the pump and nozzle. A small additional pump is necessary to remove the fluid from the vertical tube caused by splashing in the overhead chamber. The variation of the water velocity in the test section is limited. The lower limit is that velocity which is necessary to lift the water to the upper chamber⁸ and the upper limit is governed by the additional pressure which can be provided by the pump. The vacuum pump can be connected to the gas space about the vertical stream and the upper chamber. While stream energy can be recovered by this method, the disadvantages of velocity limitations and operational complexities outweigh the advantages of energy recovery, especially for a small installation.

D. The New Gottingen Cavitation Tunnel.

1. Tunnel Description.

The final design of the Gottingen tunnel employed a free jet arrangement in order to obtain very small cavitation numbers which are constant throughout the stream. While avoiding the hydrostatic pressure field of the closed jet tunnels, other disadvantages such as low energy recovery and slight bending of the streamlines had to be accepted. Figures 54 to 57 illustrate the final tunnel design. The original cylindrical chamber, having a cross-section of 1.7 square meters (18.25 square ft.) is employed as a reservoir

⁸For a height of 33 ft. of water, the lowest velocity is about 27 knots.

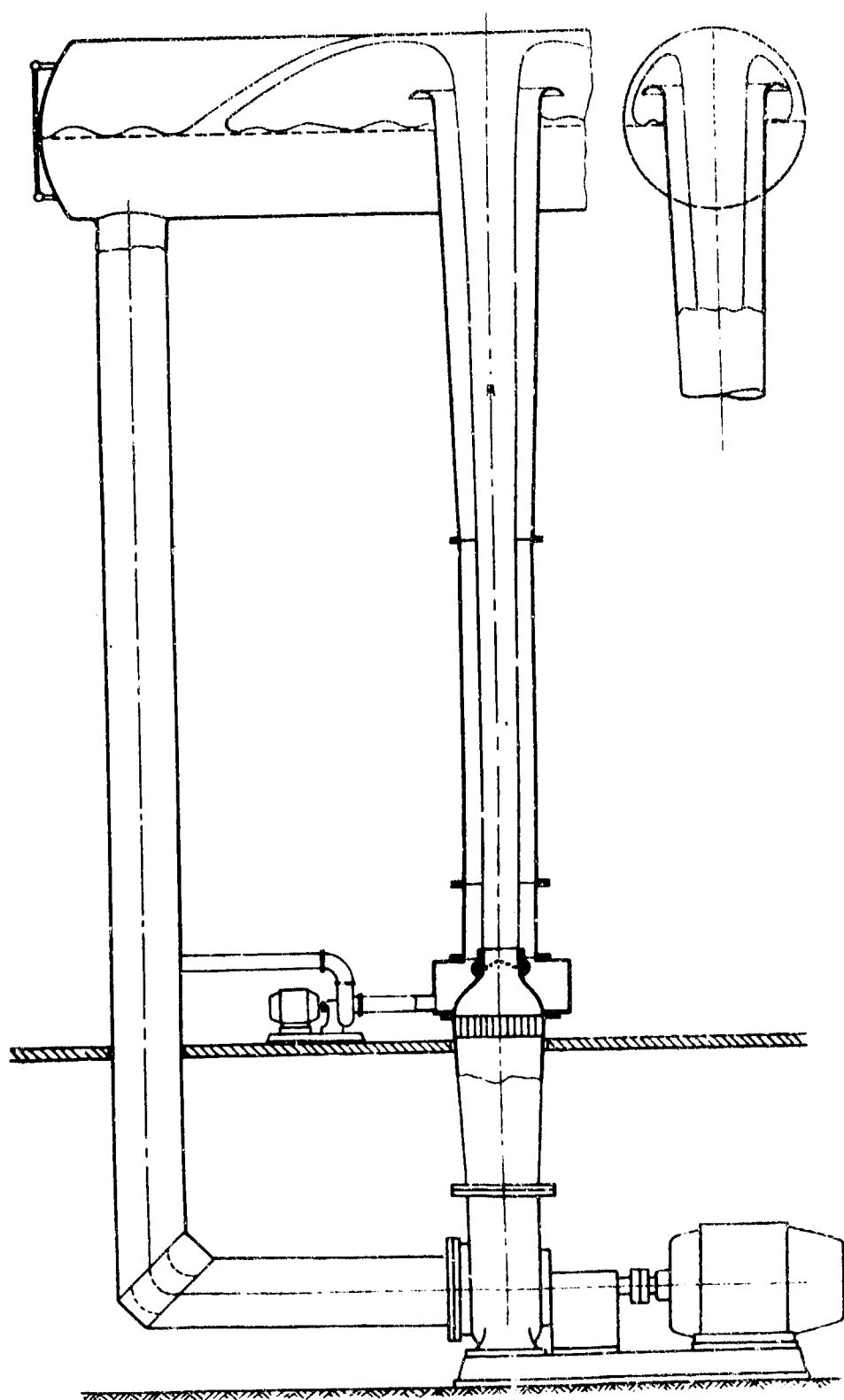


FIG. 53
FREE JET CAVITATION TUNNEL
STUDY DESIGN 103

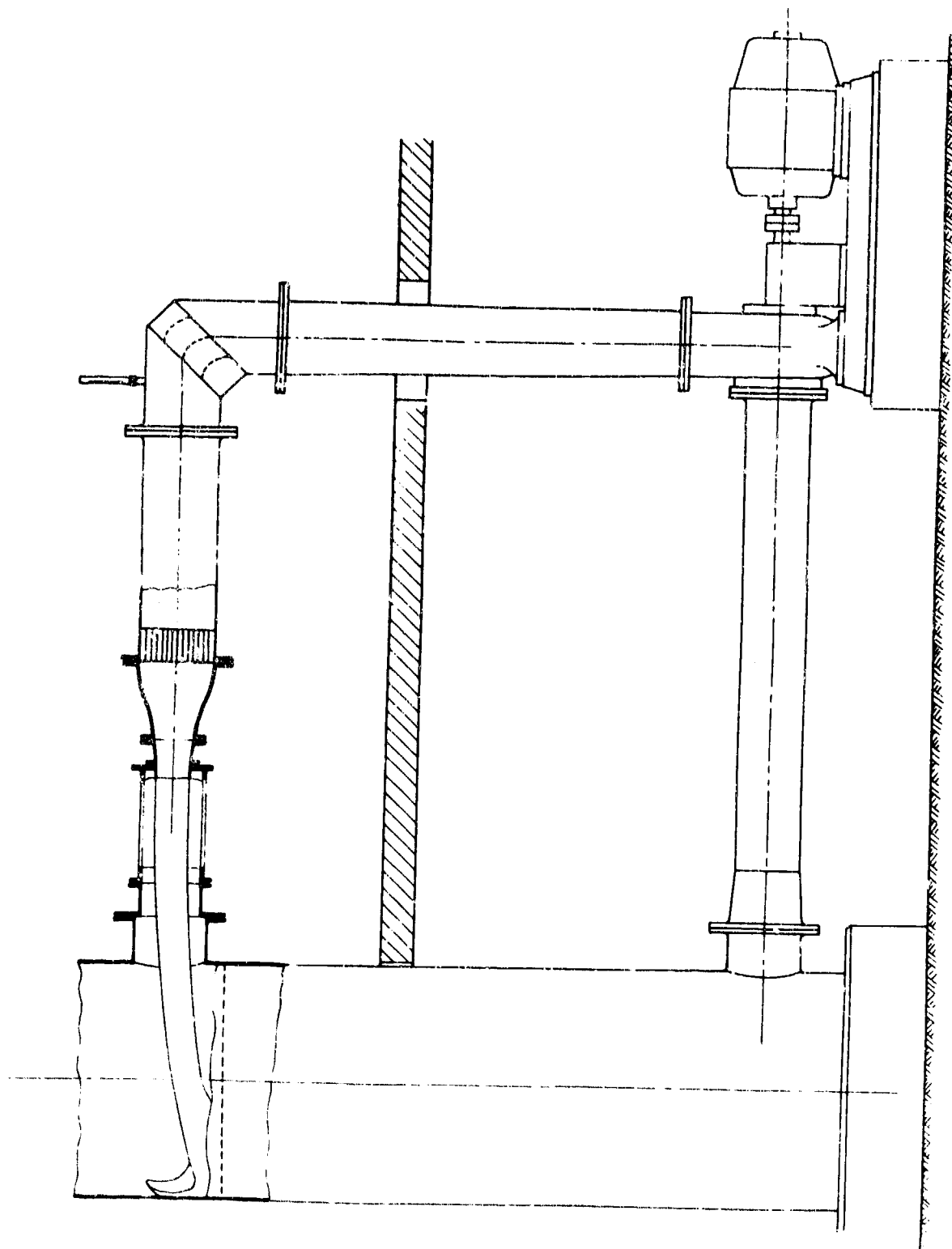


FIG. 54
NEW GÖTTINGEN FREE JET CAVITATION TUNNEL

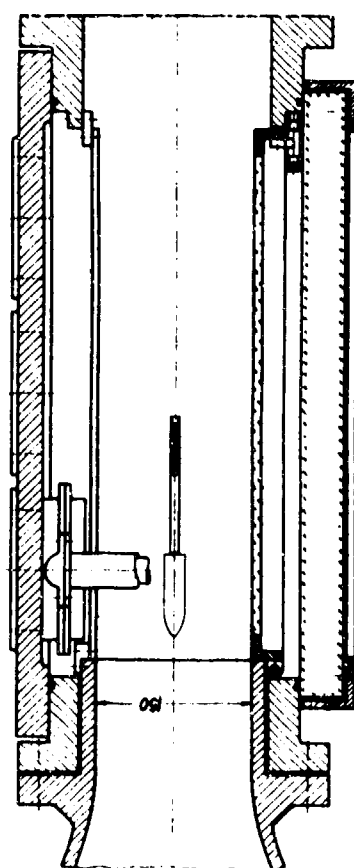
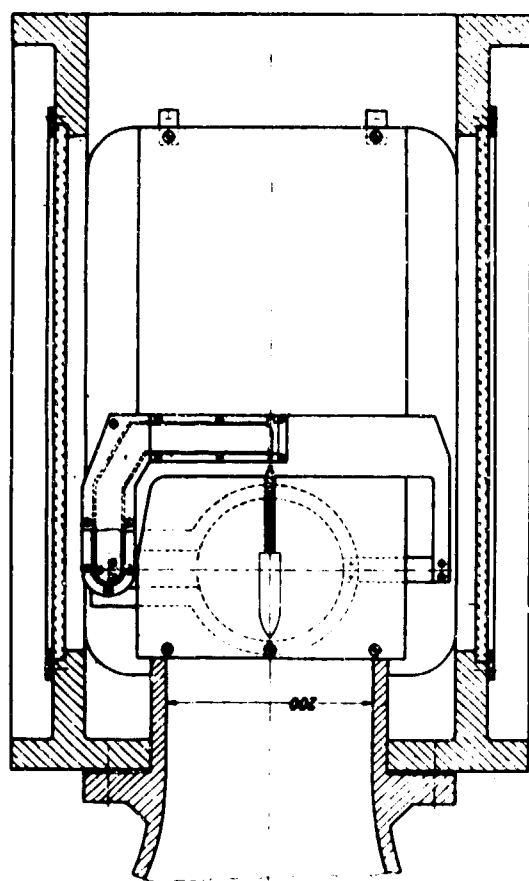
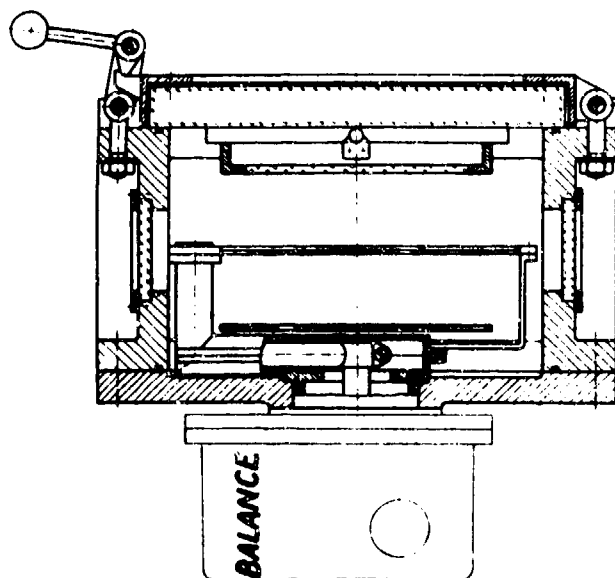


FIG. 55

NEW GÖTTINGEN CAVITATION TUNNEL TEST SECTION

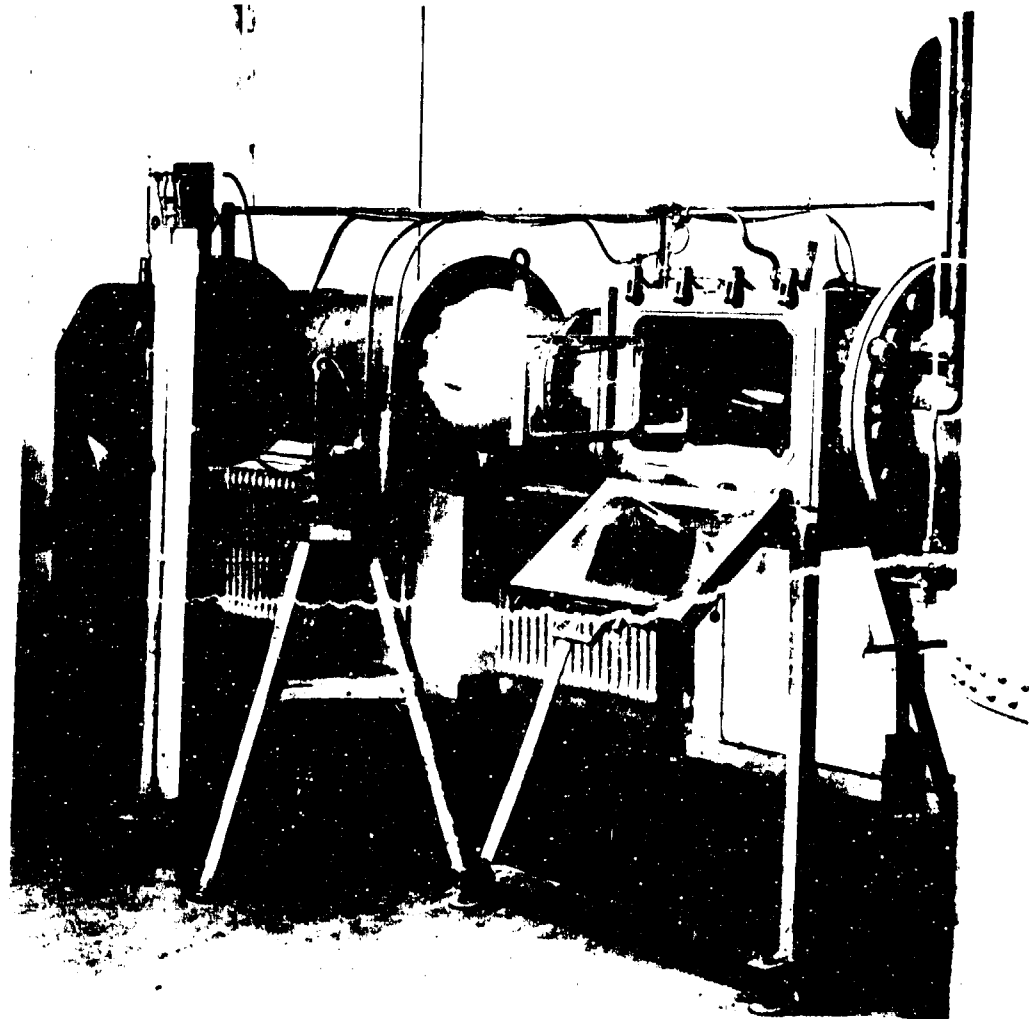


Fig. 56. GÖTTINGEN CAVITATION TUNNEL - UPPER LEVEL

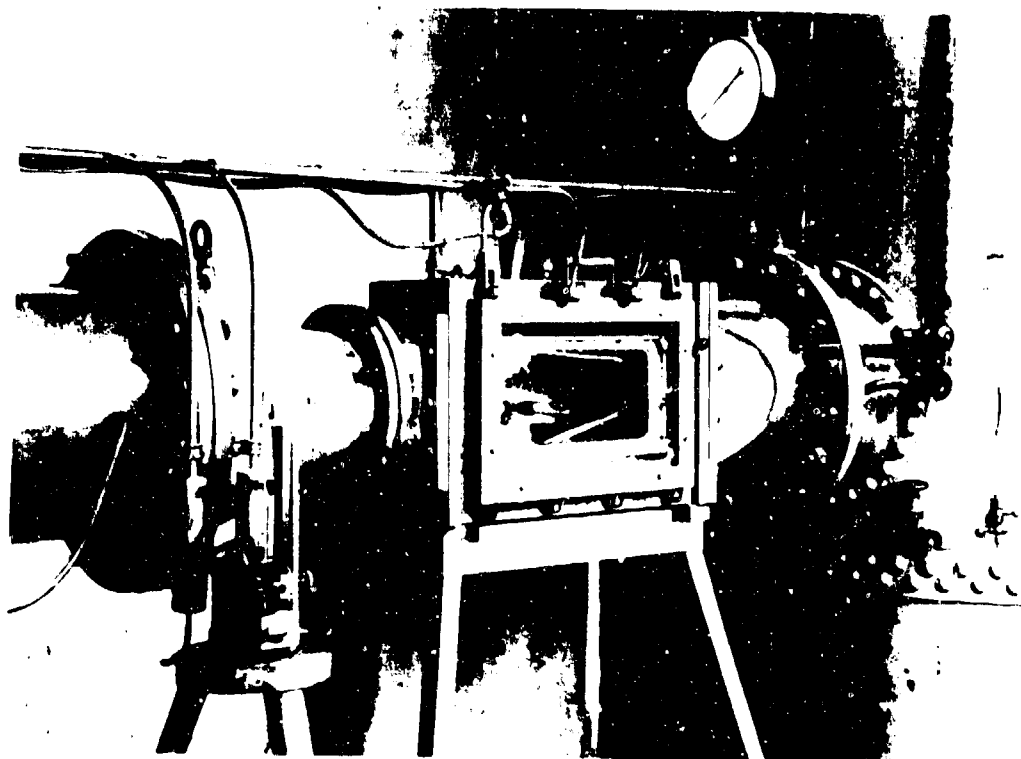


Fig. 57. GÖTTINGEN CAVITATION TUNNEL - TEST SECTION

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The Cavitation Tunnel at the Kaiser Wilhelm
Institute, Göttingen, Cont'd.

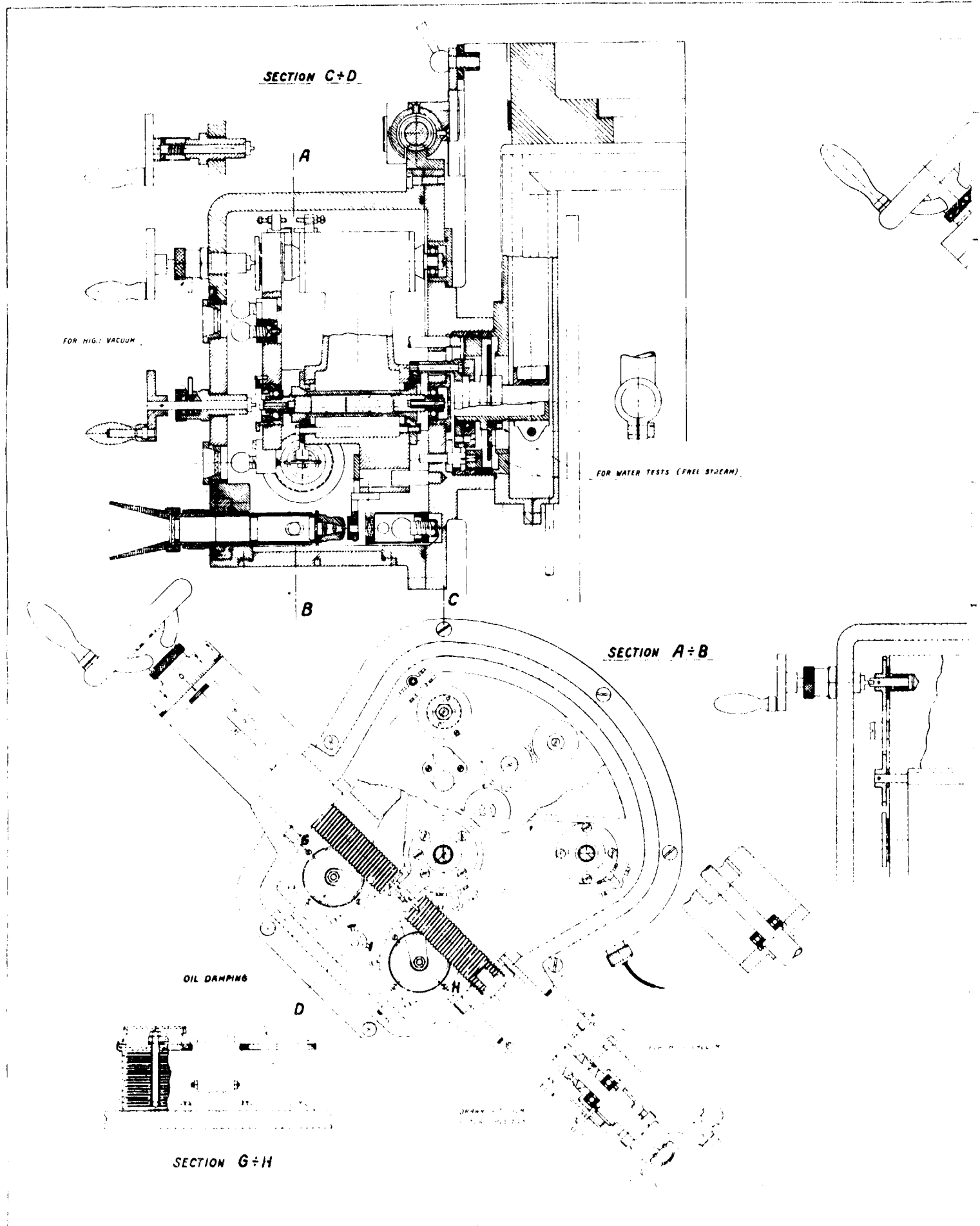
for receiving the horizontal free stream. The large sectional area of the reservoir is advantageous in preventing rapid temperature changes, avoiding fluctuations in the pressure head, and providing a low downward stream velocity to allow vapor and air bubbles to separate out of the stream. The piping sections have been enlarged to a cross-sectional area of 0.16 square meters (1.72 square feet) before the nozzle. The rectangular test section measures 0.15 meter wide by 0.2 meter high (4.92 inches by 6.55 inches) at the nozzle exit. A centrifugal pump powered by a 50 KW motor, has a normal capacity of 300 liters per second when providing a free jet velocity of 10 meters per second (19.45 knots). A conventional honeycomb is provided before the nozzle. In order to calm the flow inside the boiler, a grating is installed directly below the boiler. Without the grating, air bubbles are entrained in the stream at jet velocities greater than 5 meters per second.

The jet of the Göttingen tunnel is not completely "free" since the sides of the stream are guided by walls. The front wall is made up of a hinged glass window which can be opened for installing the model. The test section is made of light metal with the nozzle inserted at one end and the other end connected to the reservoir by an intermediate casing. The model can be lighted from above and below through plexi-glass windows in the casing and observations can be made through an airtight plexi-glass door in front.

2. Three-Component Dynamometer Installation.

The forces on a model are measured by a three-component dynamometer designed by Dr. Melchner and developed by Frossel and Kunze. As shown in Figure 58, this dynamometer is designed to measure a force component by means of a double spring system in which micrometer dials are used to determine the extension and contraction of the springs necessary to balance the applied force. An illuminated optical system is used to determine when the midpoint of the spring system is restored

DESIGNATED AT GOVERNMENT EXPENSE



REPRODUCED AT GOVERNMENT EXPENSE

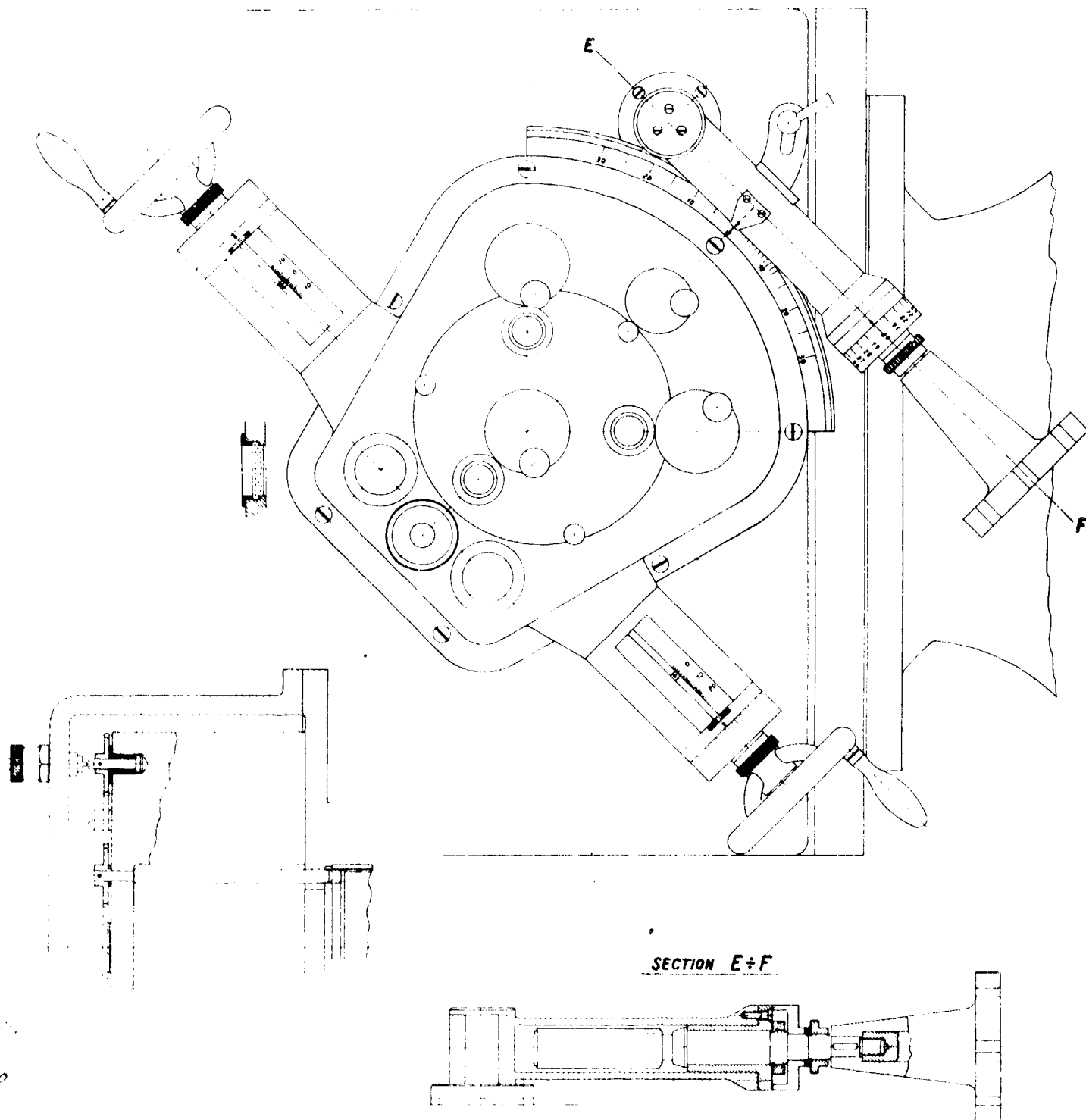


FIGURE 58

GÖTTINGEN CAVITATION TUNNEL

THREE COMPONENT DYNAMOMETER

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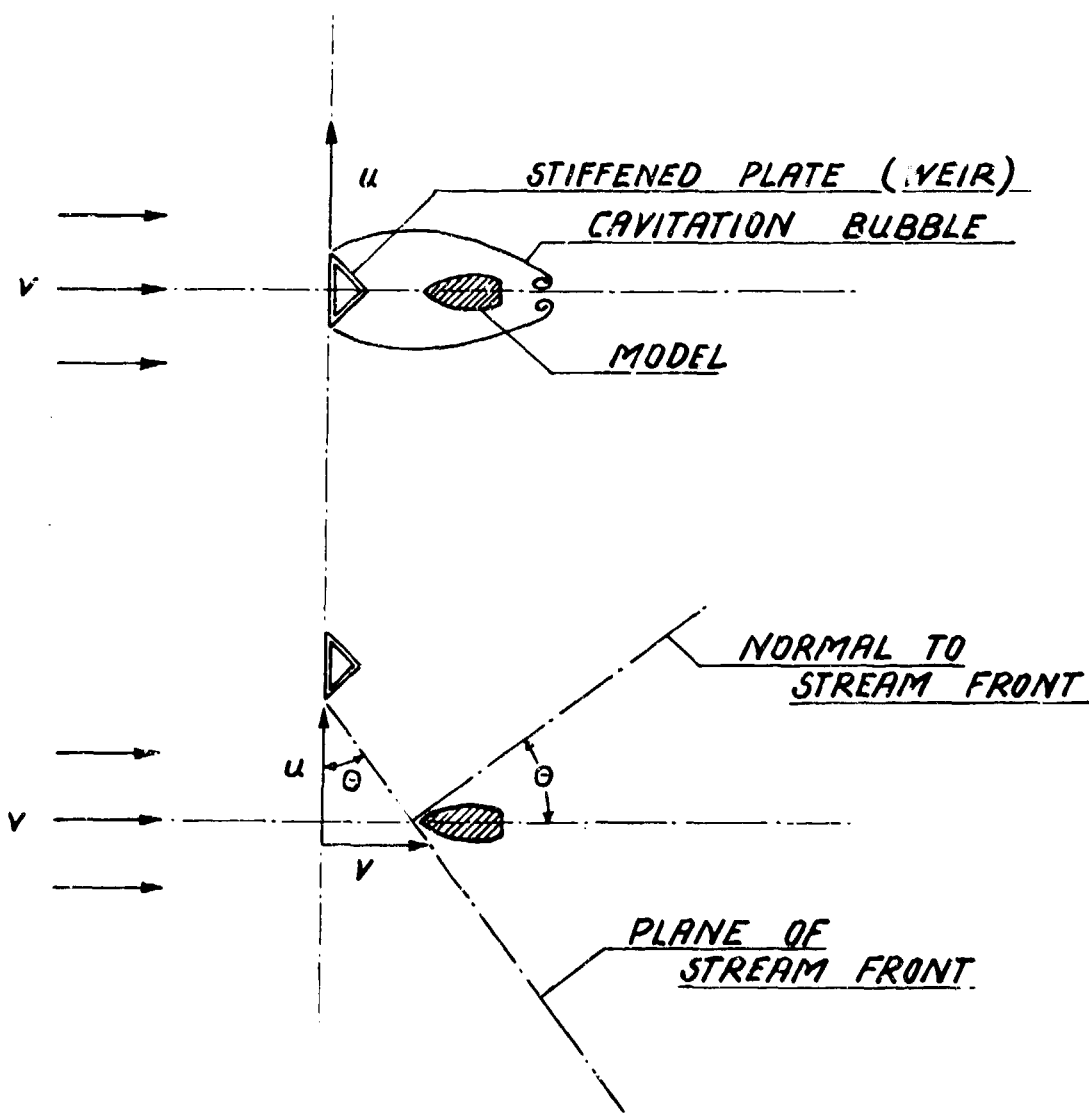
The Cavitation Tunnel at the Kaiser Wilhelm
Institute, Gottingen, Cont'd.

to its neutral or zero force position. Only one component can be measured at a time by connecting the desired pivot of the bell crank lever system while the other pivots are free. The maximum force which can be measured is about 11 pounds. The angle of attack of the model can be adjusted from $+30^\circ$ to -30° by means of a micrometer dial. Precision ball bearings are used for the pivots to reduce frictional errors.

The dynamometer can be mounted on the back wall of the test section at three locations at centerline distances of 9, 26 and 44 centimeters from the nozzle outlet. The model is supported by a rod which is connected to the movable parts of the scales by a special flat lever arrangement, as shown in Fig. 55. The lever gear is completely encased to protect it from the flow, while all other moving parts are protected against splashing by screens. The encased flat lever arrangement is arranged in the vertical centerline to pierce both surfaces for reasons of symmetry. The model is placed sufficiently in front of the lever so that the flow about the model will not be influenced. Since the stream is separated from the dynamometer by the back guide wall of the test section and the lever system penetrates the stream from above, practically no water can reach the dynamometer. In starting or stopping the pump, however, a closing arrangement is necessary, since the chamber around the test section is filled with water.

3. Tunnel Operation.

After installing the model, the forward guide window and casing are closed, the pump is cut in and the piping from the p_1 pressure tap (Fig. 51) is vented. When the stream is produced, the leakage water is drained from the casing about the test section and the closure to the dynamometer is opened. The vacuum pump is cut in next and the pressure inside the test section reduced to the desired value. The manometer for measuring $p_1' - p_b$ values first remains short-circuited to avoid water entering from the p_b opening. (See Fig. 51). After the pressure is reduced so that $\bar{C} < 0.6$, the short circuit is released and the cavitation bubble appears at the p_b hole and the manometer reads the pressure $p_1' - p_b$ or approximately $\frac{1}{2} q_0$.



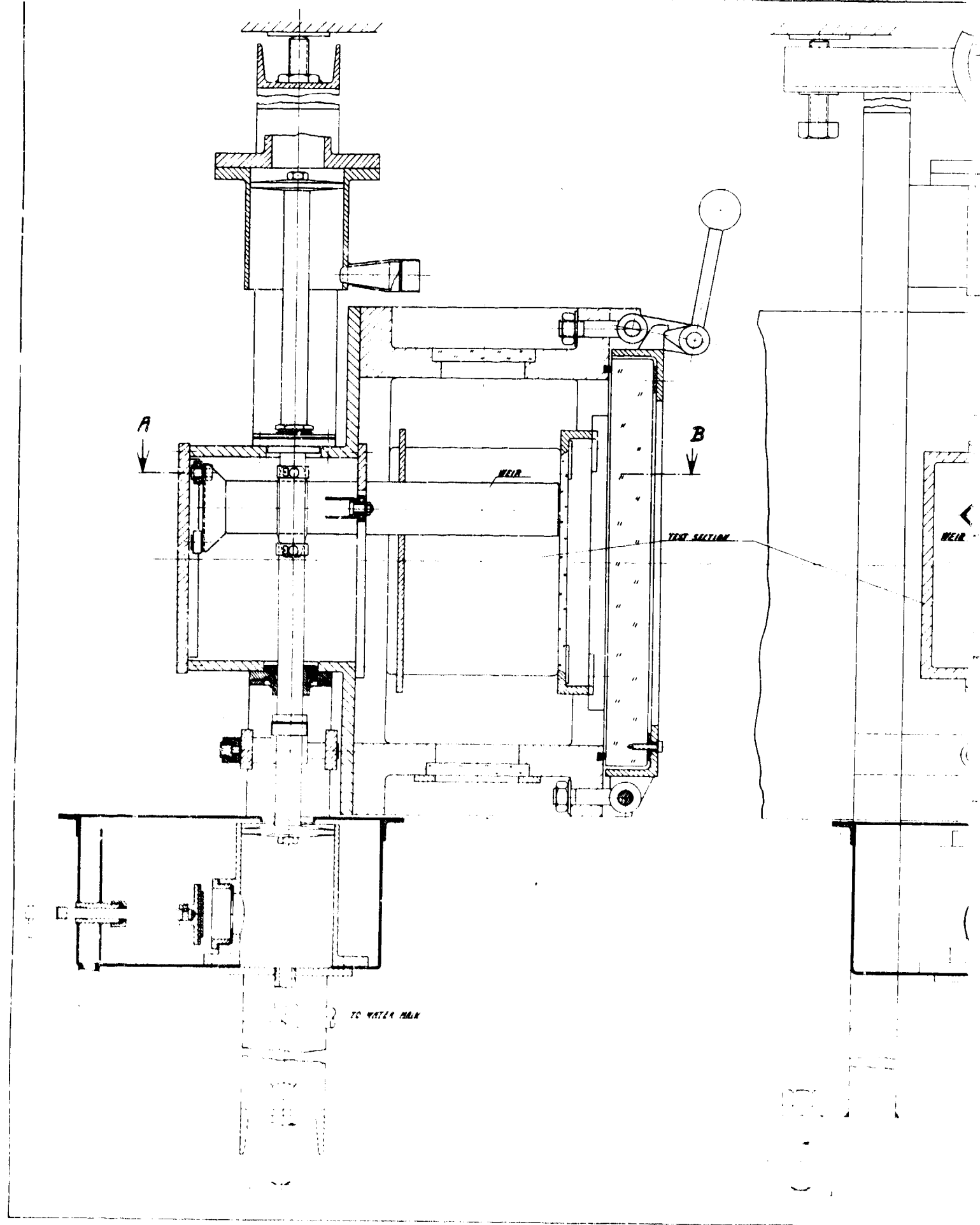
$\theta = \tan^{-1} \frac{v}{u} = \text{ANGLE OF IMPACT RELATIVE TO THE NORMAL}$

$v = \text{STREAM VELOCITY}$

$u = \text{VERTICAL VELOCITY OF PLATE}$

GÖTTINGEN CAVITATION TUNNEL
SCHEMATIC DIAGRAM OF PRINCIPLE
OF AIR-WATER ENTRY APPARATUS
 FIGURE 59

DO NOT COVER MULTIPLE EXPENSE



REPRODUCED AT GOVERNMENT EXPENSE

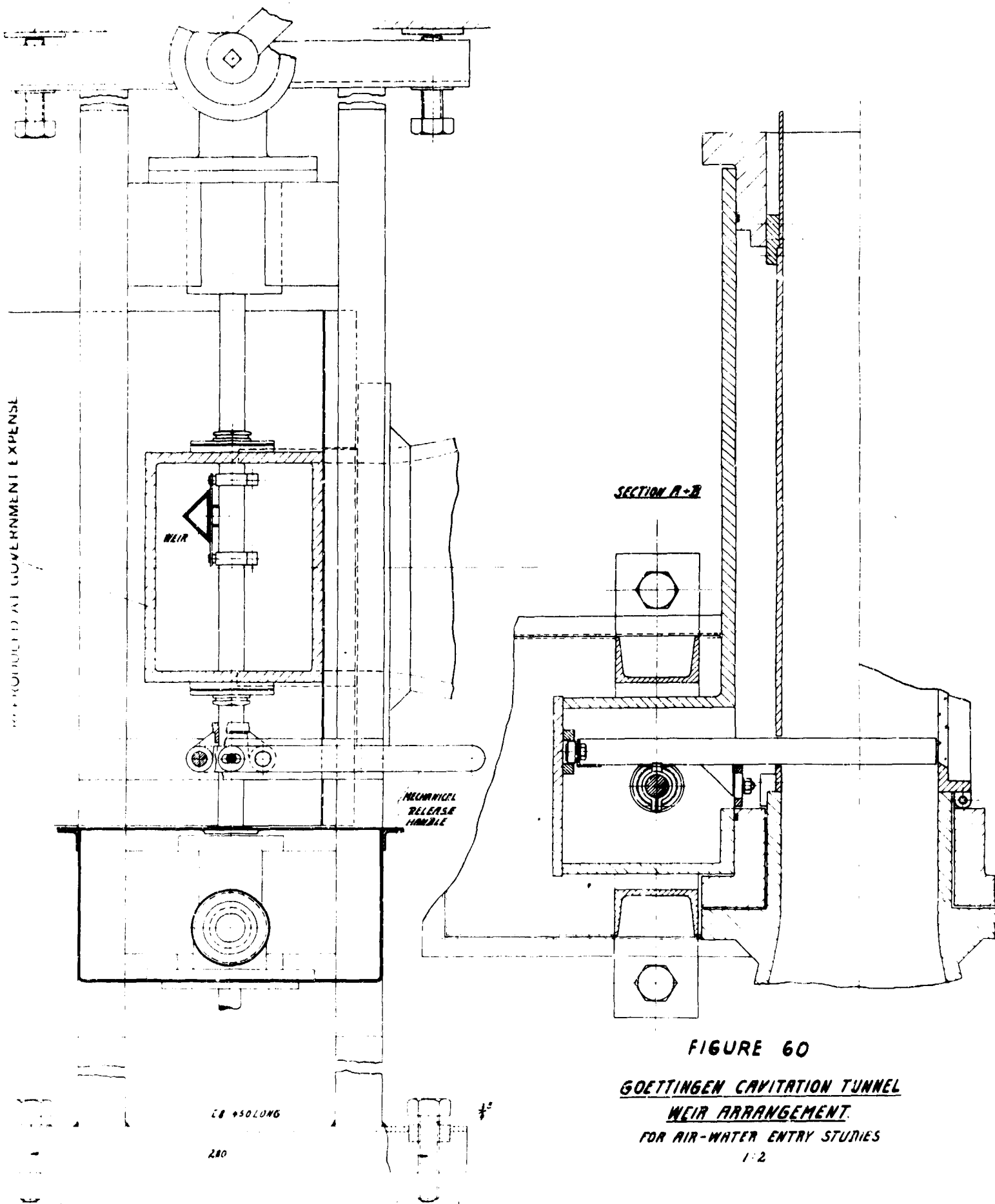


FIGURE 60
GOETTINGEN CAVITATION TUNNEL
WEIR ARRANGEMENT.
FOR AIR-WATER ENTRY STUDIES
1/2

RESTRICTED.

The Cavitation Tunnel at the Kaiser Wilhelm
Institute, Göttingen, Cont'd.

large elaborate equipment. An apparent advantage is that a high speed motion picture camera could be placed in a single location to record the complete entry cycle pictorially. Difficulties could be expected in controlling the shape of the stream front and, consequently, in determining the correct impact angle.

5. Cavitation Projects.

In addition to utilizing the Göttingen cavitation tunnel for air-water entry studies, other new fields of development and research were undertaken by means of cavitation bubble investigations. In order to reach as high flight speeds as possible without locally exceeding the velocity of sound, airplane forms such as Me-262 were tested to determine the form which showed no noticeable cavitation at low cavitation numbers. As an immediate method of determining approximate constant pressure surfaces, the form of an appropriate cavitation bubble was determined when using a model consisting of the cowl and the wing leading edges only. The abrupt discontinuity of the wing section behind the leading edge induced a cavitation bubble whose form at various longitudinal sections could be recorded by stereoscopic photographs, or by ordinary photographs in which the bubble interfaces were illuminated by a thin line light source from above. By using the cavitation bubble as an approximate constant pressure surface, new forms of engine cowlings were also developed. The usefulness of the forms of cowlings determined by cavitation investigations was confirmed by pressure distribution measurements in the wind tunnel. In addition, cavitation investigations for the determination of the form of the transition from the wing to the fuselage and from the wing to the engine nacelle had been started.

Through the commission of the Chemical-Physical Research Institute of the German navy, investigations of model underwater rocket projectiles were undertaken in the cavitation tunnel to observe the flow and record three-component measurements for determination of drag and stability. The problem of instability of the underwater projectiles had not been solved.

RESTRICTED.

The Cavitation Tunnel at the Kaiser Wilhelm
Institute, Göttingen. Cont'd.

General research studies of cavitation bubbles behind different bodies were underway to determine the cross section of the cavitation bubble as a function of the body drag. Also the contours of axially symmetric cavitation bubbles with nearly constant pressure distribution had been calculated by the source-sink method. It was determined that the longitudinal sections of the elongated bubble at low cavitation numbers could be represented approximately by the generalized ellipse:

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^{2.4} = 1, \text{ where}$$

a = major radius

b = minor radius

VI. Cavitation Tunnel at J.M. Voith Maschinen-
fabriken, Heidenheim.

A. Description.

About 1937 a closed circuit cavitation tunnel was erected at the Brunnenmühle research plant of the firm J. M. Voith for the purpose of testing model Voith-Schneider propellers at reduced pressures. The tunnel is of welded plate construction in the usual vertical ring shape. The lower horizontal leg and the vertical legs are circular in cross section, but at the upper elbow before the test section, the cross section becomes rectangular. All of the corners are well-rounded without guide vanes, except the upper corner before the measuring section. Fig. 61 shows the four guide vanes in the square upper elbow before the test section and two guide plates in the converging nozzle.

Power for circulating the water is supplied by a 16 H.P. motor driving a controllable-pitch kaplan turbine pump of 0.5 m. (19.68 in.) diameter. The lower horizontal leg is located 10 m. (32.8 ft.) below the upper leg in order to prevent air being sucked in at the pump stuffing box and to preclude cavitation on the pump blades.

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Cavitation Tunnel at J. M. Voith Maschinenfabriken,
Heidenheim. Cont'd.

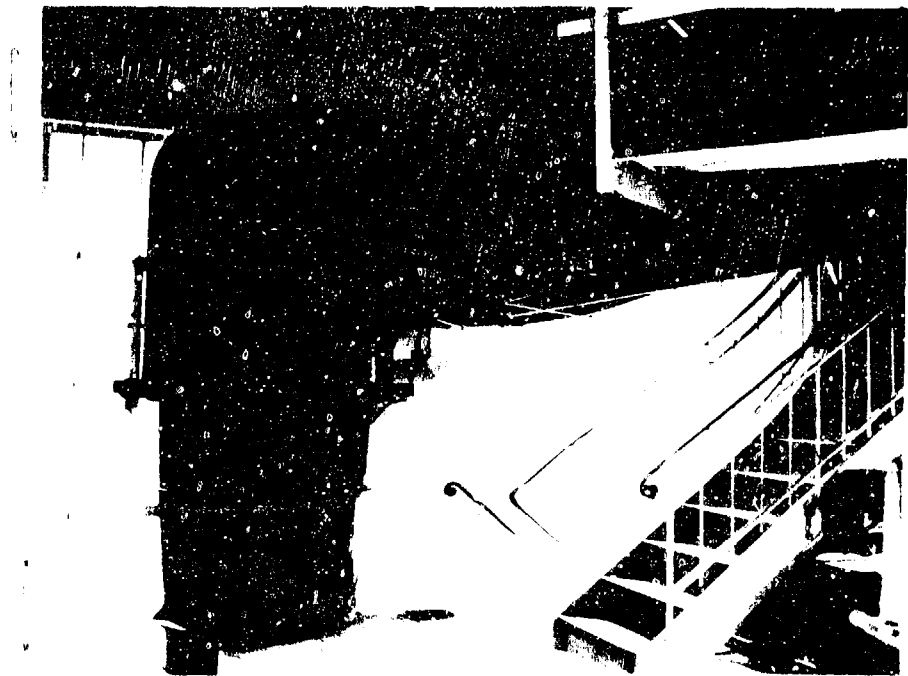


Fig. 61.

VOITH CAVITATION TUNNEL.

The upper elbow before the converging nozzle indicates the welding for the four guide vanes. The location of two additional guide plates can be seen on the converging nozzle section.

RESTRICTED.

Cavitation Tunnel at J.M. Voith Maschinenfabriken,
Heidenheim. Cont'd.

The test section is rectangular with width 0.70 m. (27.56 in.) and height 0.25 m. (9.84 in.). The maximum water speed in the test section is 1.6 m/sec (3.11 knots).

Over the test section is mounted a cylindrical chamber which houses the dynamometer. (Fig. 62). Several glass ports are installed in the chamber casing for reading the dynamometer. A small vacuum pump is also connected to the chamber for reducing the pressure over the free surface.

Since the direction of the thrust of a Voith-Schneider propeller is normal to the rotation axis, it is not possible to transmit the thrust and torque through the same shaft. Fig. 63 shows the dynamometer and propeller installation in the chamber. The dynamometer motor-model propeller assembly is suspended by cables so that there is an annular clearance inside the chamber. The whole frame can be returned to the center position by a calibrated spring; the spring tension, which is relative to the thrust, can be read on the scale outside the casing. The driving motor stator is suspended so that it can swing about its own axis against a resisting spring force; the angular distortion, which is relative to the torque, can be read directly from the outside of the chamber through a peep hole. Since the model cavitation propeller is only 0.2 m. (7.87 in.) in diameter with 0.126 m. (4.96 in.) length of blades, the dynamometer power can be supplied by a 1 H.P. motor.

Based on the work of Vuskovic (5), Dr. Müller of the Voith research plant considers that the effects of the air content of the tunnel water are negligible. When new water is added, the water is circulated for about five hours to remove entrained air and to reduce the content of dissolved air to a low value.

B. Representation of Test and Calculated Results.

Since the ratio of the model propeller area to the tunnel test section area is 0.14 the results of the cavitation

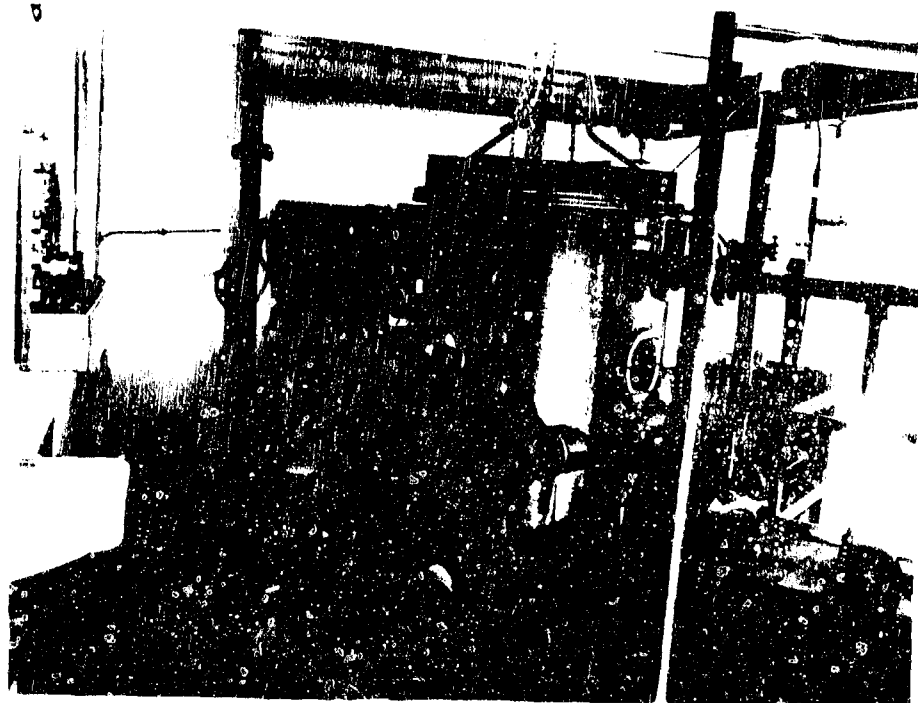


FIGURE 62
VOITH CAVITATION TUNNEL, JUNE 1945
TEST SECTION AND DYNAMOMETER CHAMBER

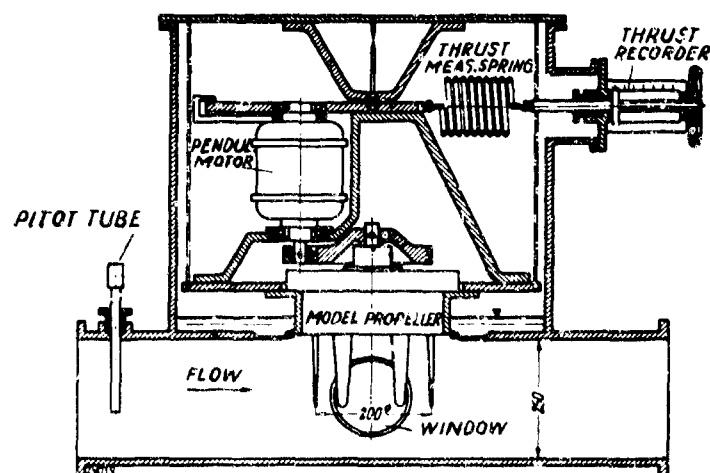


FIGURE 63
VOITH CAVITATION TUNNEL DIAGRAMMATIC ARRANGEMENT OF
DYNAMOMETER AND MODEL VOITH-SCHNEIDER PROPELLER

RESTRICTED.

Cavitation Tunnel at J. M. Voith Maschinenfabriken,
Heidenheim. Cont'd.

tests are corrected to the values for infinite extended flow by the method of Hood and Harris (9). The cavitation number is calculated from the formula

$$\sigma = \frac{p_s - p_v}{\rho/2 \cdot v_a^2}$$

where p_s = the static pressure at the skin of the ship
at the propeller location,

p_v = vapor pressure

ρ = mass density of the water.

v_a = speed of advance.

The thrust load coefficient used at the Voith research plant

is defined as $C_L = \frac{T}{\rho/2 \cdot v_a^2 A_p}$

where T = thrust

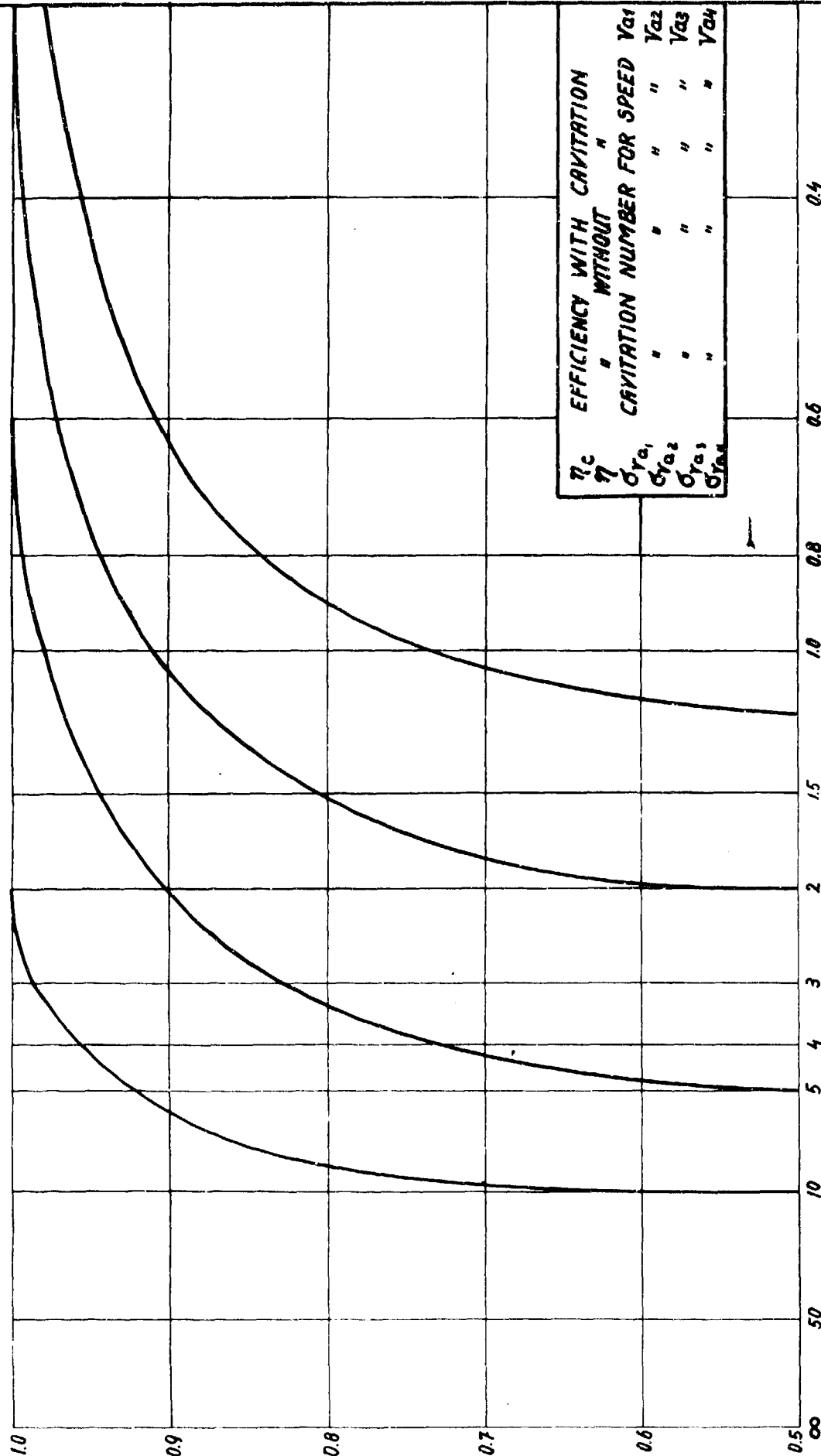
ρ = mass density of the water

v_a = speed of advance, and

A_p = propeller area = blade circle diameter x blade
length for a Voith-Schneider propeller.

The test results are plotted as curves of constant cavitation numbers, with the ratio of efficiency with cavitation to efficiency without cavitation as the ordinate, and the thrust load coefficient C_L as the abscissa. A sample diagram of this method of presenting cavitation test results is shown in Fig. 64. This method was chosen so that the efficiency diminution for a given flow condition, defined by C_L and σ , can be seen at once, and an immediate decision can be reached as to whether the cavitation influence can be eliminated by enlarging the propeller.

INFLUENCE OF CAVITATION ON EFFICIENCY FOR A VOITH SCHNEIDER PROPELLER



THRUST LOAD COEFFICIENT $C_t \cdot \frac{T}{\rho g D^4 \cdot \gamma_a^2 \cdot A_p}$

FIGURE 164

RESTRICTED.

Cavitation Tunnel at J. M. Voith Maschinenfabriken,
Heidenheim. Cont'd.

The influence of cavitation of a Voith-Schneider propeller on the steering forces depends on the steering angle, α , as well as the thrust load coefficient C_L , where the steering angle α is defined as the angle of the propeller steering point from the ahead drive position. The cavitation influence for steering angles up to 15° can be determined from tests in the cavitation tunnel, but with larger steering angles up to 90° , the flow breaks away from the suction sides of the blades because of the high angle of attack; in this case the influence of the tunnel walls on the flow configuration becomes unduly great. For steering angles greater than 15° , Dr. Muller calculates the resulting blade force by a method of Betz. The dimensionless normal force coefficient is calculated by the formula:

$$C_N = \frac{2 \pi \sin \alpha}{4 \pi \sin \alpha} + \frac{P_s - P_v}{\rho/2 \cdot v_r^2}$$

where α = angle of attack

P_s = static pressure at the hull surface in the plane of the V.S. propeller.

P_v = vapor pressure

ρ = mass density of water

v_r = resultant flow velocity to the blade profile.

The first term is the normal force coefficient of Kirchhoff resulting from the positive pressure on the pressure side of the profile. The second term is the cavitation number, or the additional normal force coefficient resulting from the vapor pressure on the suction side of the profile when there is complete suction side cavitation. The resulting transverse force of the propeller can be obtained by graphical determination of the blade forces on the whole blade circle in combination with the proper number of blades. From airfoil data, the transverse force can be calculated without cavitation, and thereby the reduction of the transverse force due to cavitation can be determined. Such a calculation is

RESTRICTED.

Cavitation Tunnel at J. M. Voith Maschinenfabriken,
Heidenheim. Cont'd.

important for determining the steering force of a Voith-Schneider propeller when delivering no thrust, which is the case when a ship moves transversely to a dock.

VII. Cavitation Tunnels Designed by H.S.V.A. for
Russia, Japan and Sweden.

A. Russian Cavitation Tank.

In 1932, H.S.V.A. designed a cavitation tunnel for the Leningrad Model Basin in Russia. The tunnel was constructed by Blohm and Voss in Hamburg and the measuring instruments were designed and constructed by H.S.V.A. The erection of the tunnel was under the supervision of Ing. Hoppe of H.S.V.A. The tunnel dimensions, characteristics, and measuring instruments were the same as the original unaltered H.S.V.A. cavitation tunnel I described in Part II, except that the propeller pump motor R.P.M. was 1930 instead of 820. A reduction gear of ratio 6.45 to 1 reduced the pump R.P.M. to 300, the same as H.S.V.A. cavitation tunnel I. A diagrammatic drawing of the Russian tank is shown in Fig. 65.

B. Japanese Cavitation Tank.

A cavitation tunnel for Japan was designed by H.S.V.A. in 1935 to meet the following specifications:

1. The velocity in the test section shall be at least 6 m/sec (11.7 knots).
2. The test section diameter shall be sufficient for testing a model propeller of diameter 0.3 meters (11.81 in.).
3. The propeller dynamometer R.P.M. shall be at least 2400 R.P.M.
4. The thrust and torque dynamometers shall be self-recording.

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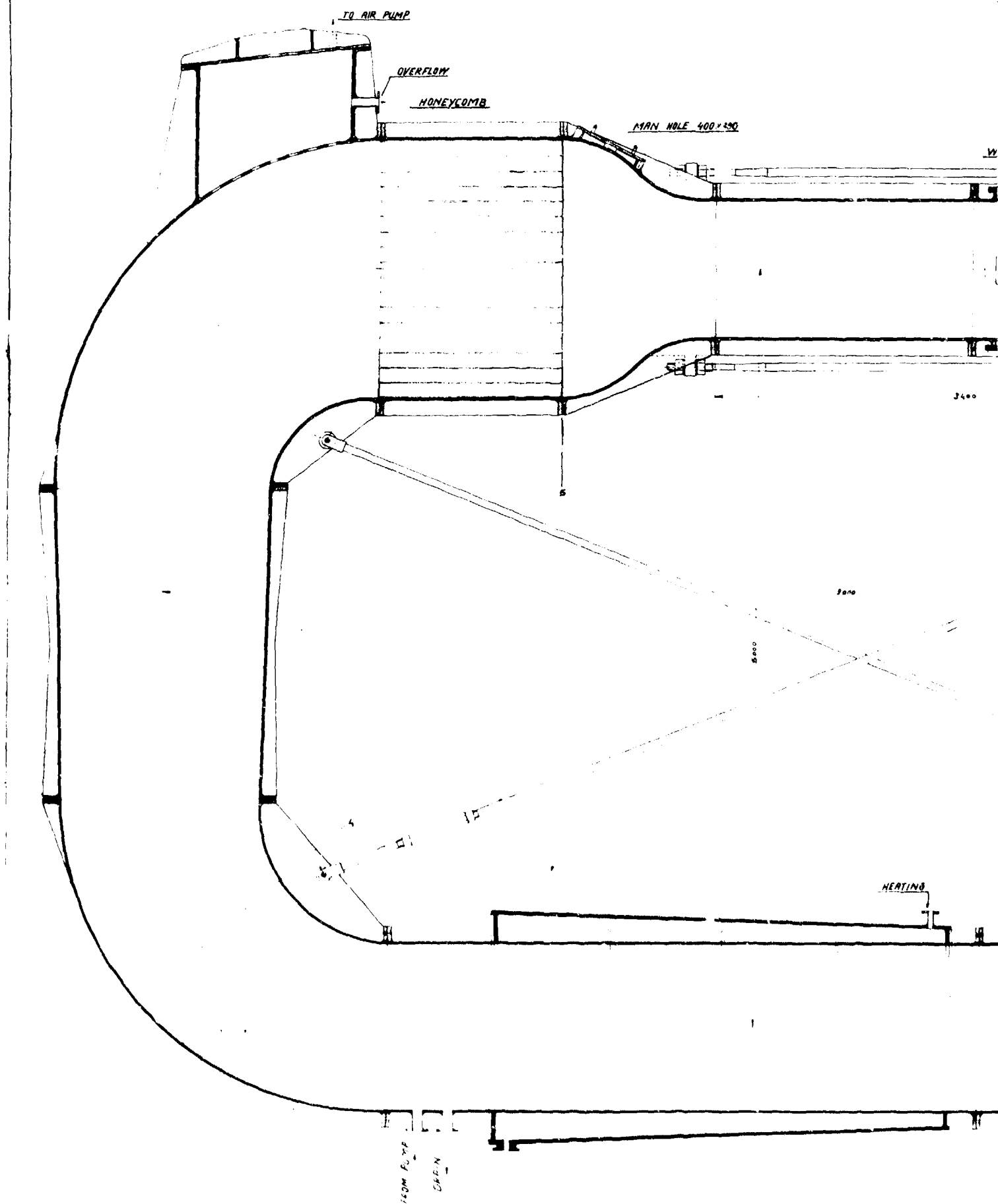
Cavitation Tunnels Designed by H.S.V.A. for Russia,
Japan and Sweden. Cont'd.

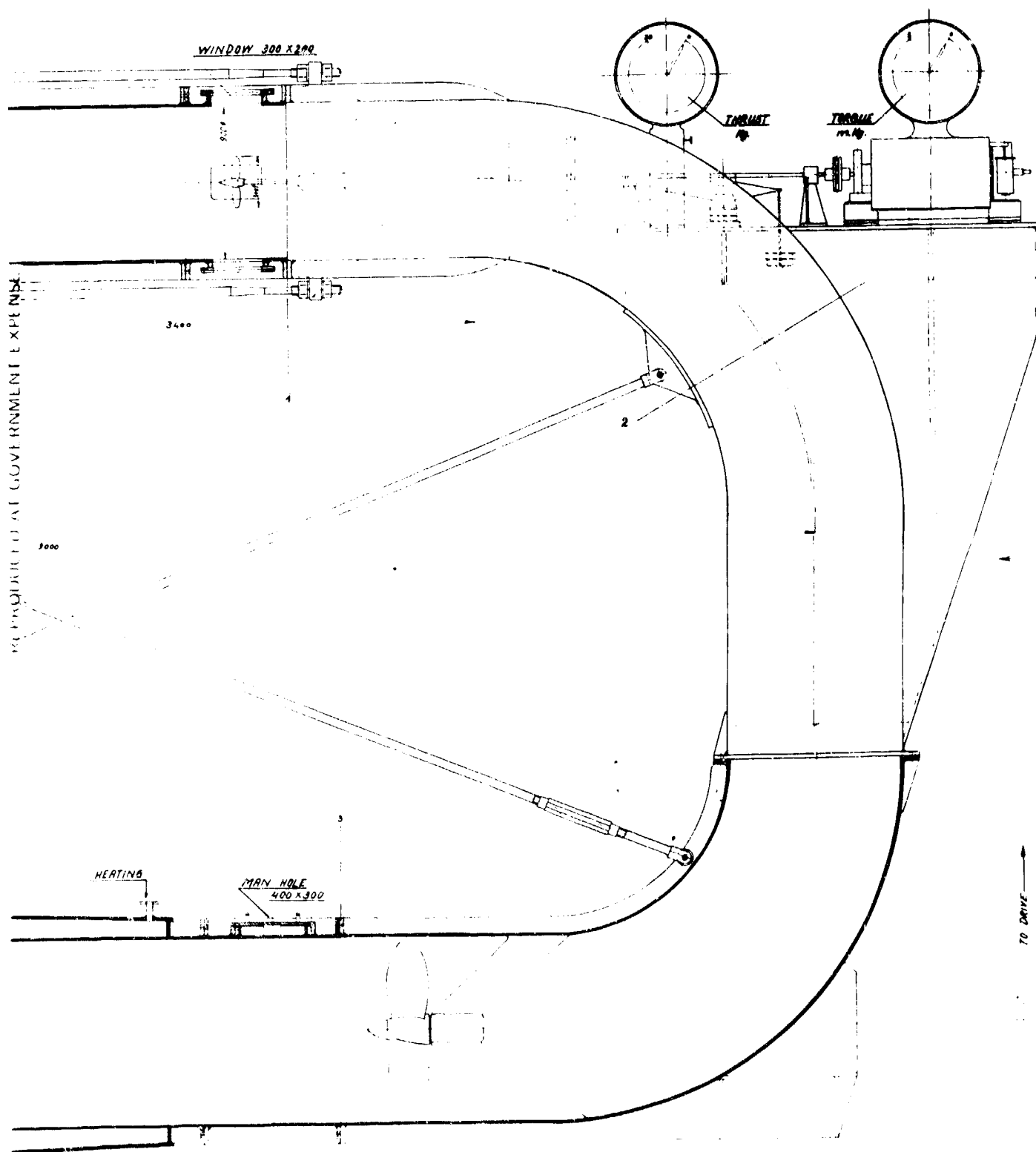
Based on previous experiences with H.S.V.A. cavitation tunnel I, the Japanese tunnel was designed with a well-rounded divided elbow downstream from the test section. (Fig. 66). No honeycomb or radial guide vanes were installed before or after the propeller pump, but a long honeycomb was installed before the nozzle. Rectangular sections with rounded corners were used throughout the circuit except in the vicinity of the pump, where the sections were circular. The test section was made square with rounded corners, 0.9 meters (35.43 in.) on a side, and with a length of 3.4 meters (11.16 ft.). The actual pump power, dynamometer power, and water velocity in the test section are not known at this writing, but it is believed that the test section velocity is in the range of 8 to 9 meters per second (15.5 to 17.5 knots).

The conventional Hamburg double shaft arrangement was not used for the dynamometer installation for the Japanese tunnel. A single shaft transmits the thrust and torque of the model propeller to the dynamometer (Fig. 67). A conventional thrust balance scale with a large dial for direct reading was installed, together with a transmitter and an electrical thrust recording instrument manufactured by Hartmann and Braun in Frankfurt. The dynamometer motor was mounted as a pendulum motor so that the reaction of the stator can be transmitted through a beam scale, and the torque read directly on a large dial. A dial type electrical tachometer was installed for reading the propeller R.P.M. directly. Electrical transmitters and recorders were also included for recording the propeller R.P.M. and torque. The conventional Hamburg compensating chamber was omitted. Except for the recording equipment, the simple dynamometer arrangement is similar to that used for the cavitation tunnels at the Taylor Model Basin in Washington, in contrast to the usual more complicated Hamburg design for eliminating thrust and torque corrections.

While the test section diameter of the Japanese tunnel is the same as the tunnel at Wageningen, the vertical distance between the upper and lower horizontal sections is only 5 m. (16.4 ft) as compared to 7 m. (22.96 ft.) for the Wageningen tunnel.

REPRODUCTION OF GOVERNMENT EXPENSE





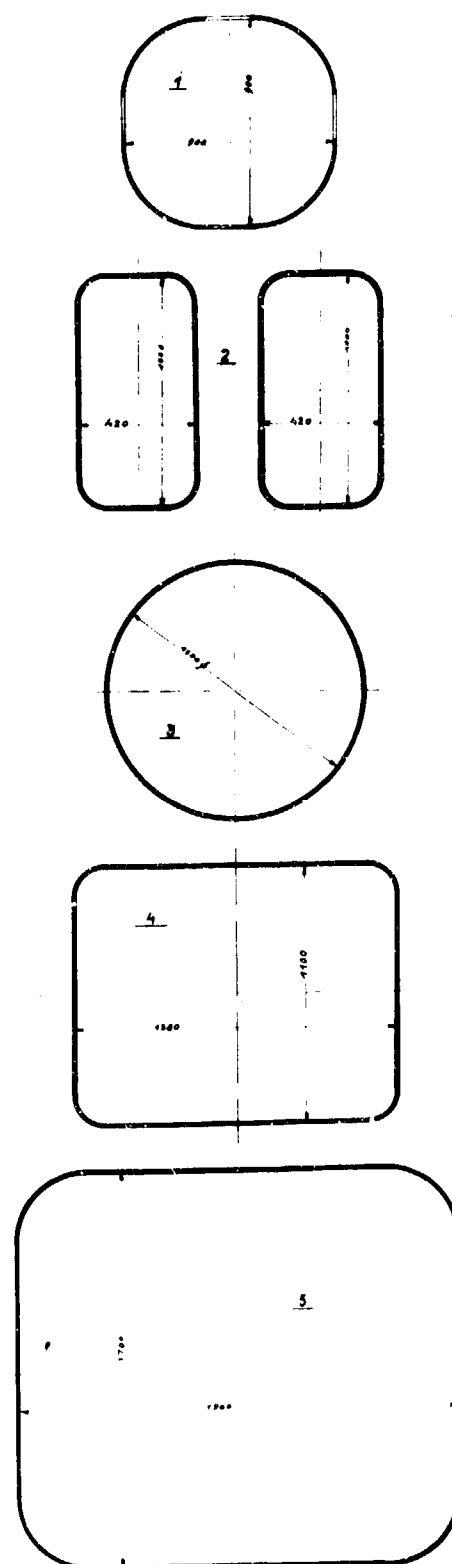
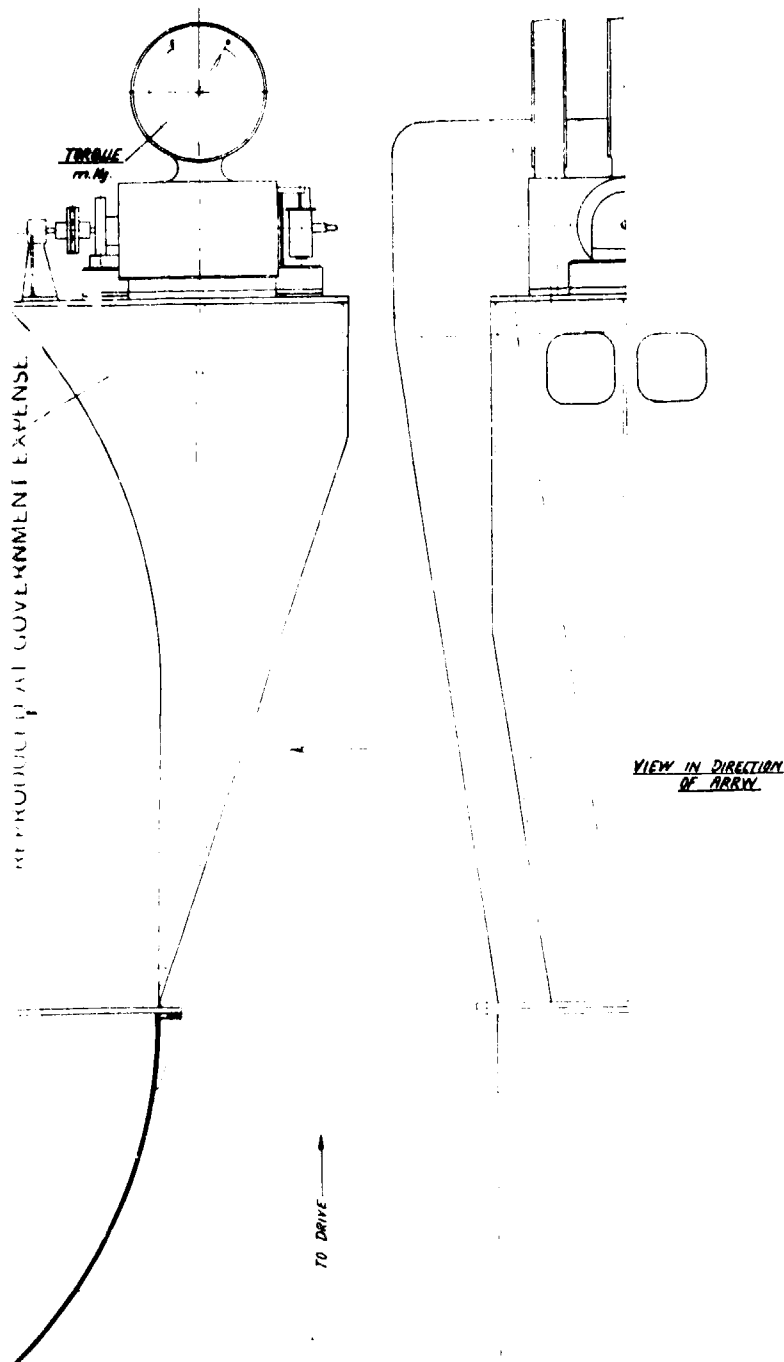
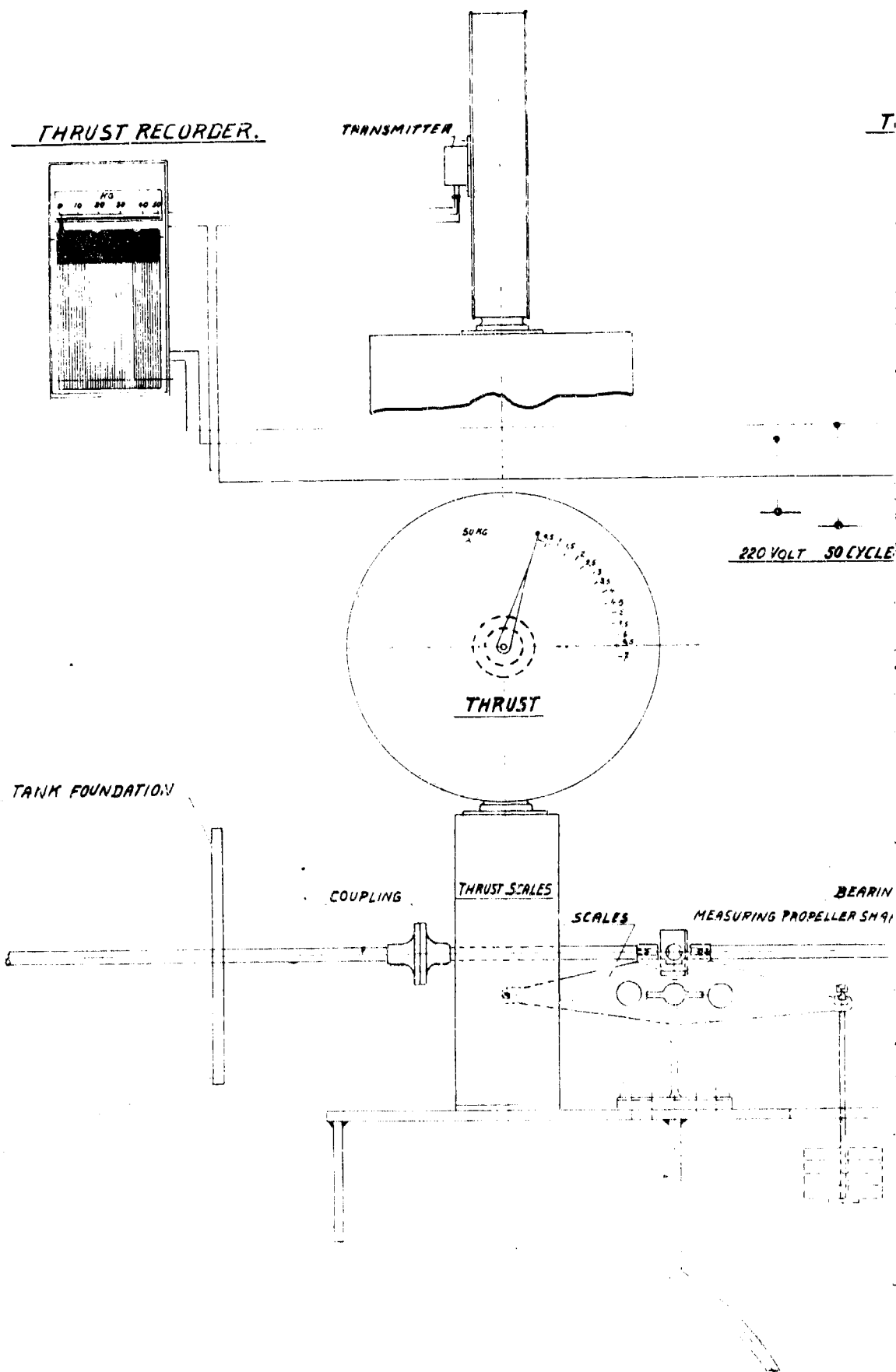


FIGURE 66

CAVITATION TUNNEL FOR JAPAN
DESIGNED BY H.S.Y.A
ASSEMBLY AND SECTIONS

REPRODUCED AT GOVERNMENT EXPENSE



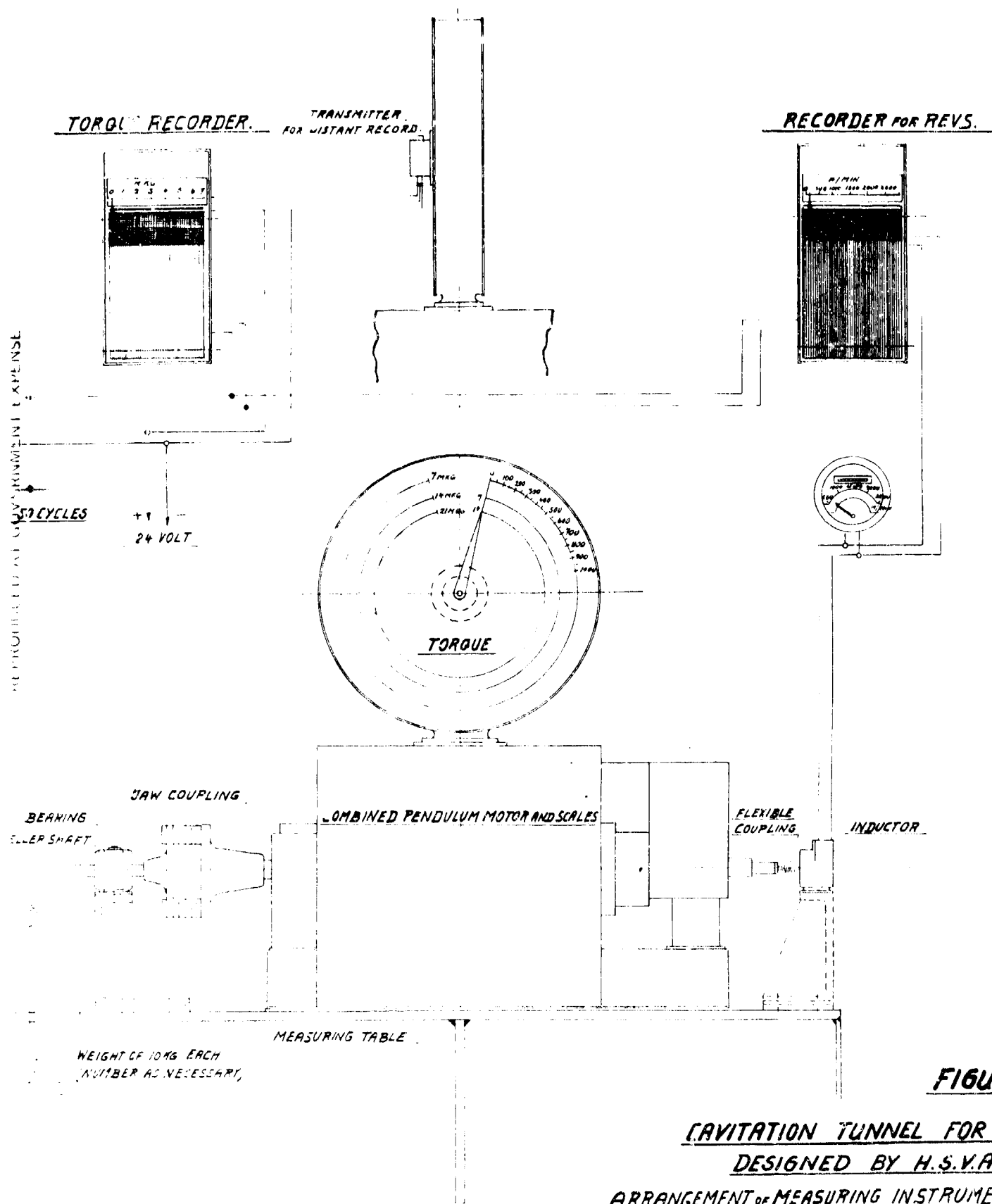


FIGURE 67

CAVITATION TUNNEL FOR JAPAN
DESIGNED BY H.S.V.A.

ARRANGEMENT OF MEASURING INSTRUMENTS

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Cavitation Tunnels designed by H.S.V.A. for Russia,
Japan and Sweden. Cont'd.

C. Cavitation Tank at Karlstads Mekaniska Verkstad,
Kristinehamn, Sweden.

The most modern cavitation tunnel designed by H.S.V.A. was constructed for the Karlstad Mekaniska Verkstad at Kristinehamn, Sweden in 1942. This tunnel, shown in Fig. 68, has been described in a recent publication (10). The principal characteristics are as follows:

Test Section

Width	0.8 m	(31.5 in.)
Height	0.8 m	(31.5 in.)
Area	0.555 m ²	(5.98 ft. ²)
Length	about 1.0 m.	(39.37 in.)
Maximum water velocity	9m/sec	(17.5 knots)

Vertical height between upper and lower legs 5.0m (19.68 ft.)

Driving Motor

Horsepower	150
Voltage	380
R.P.M.	25 to 920 ahead, 250 reverse

Reduction gear ratio $920/380 = 2.42$

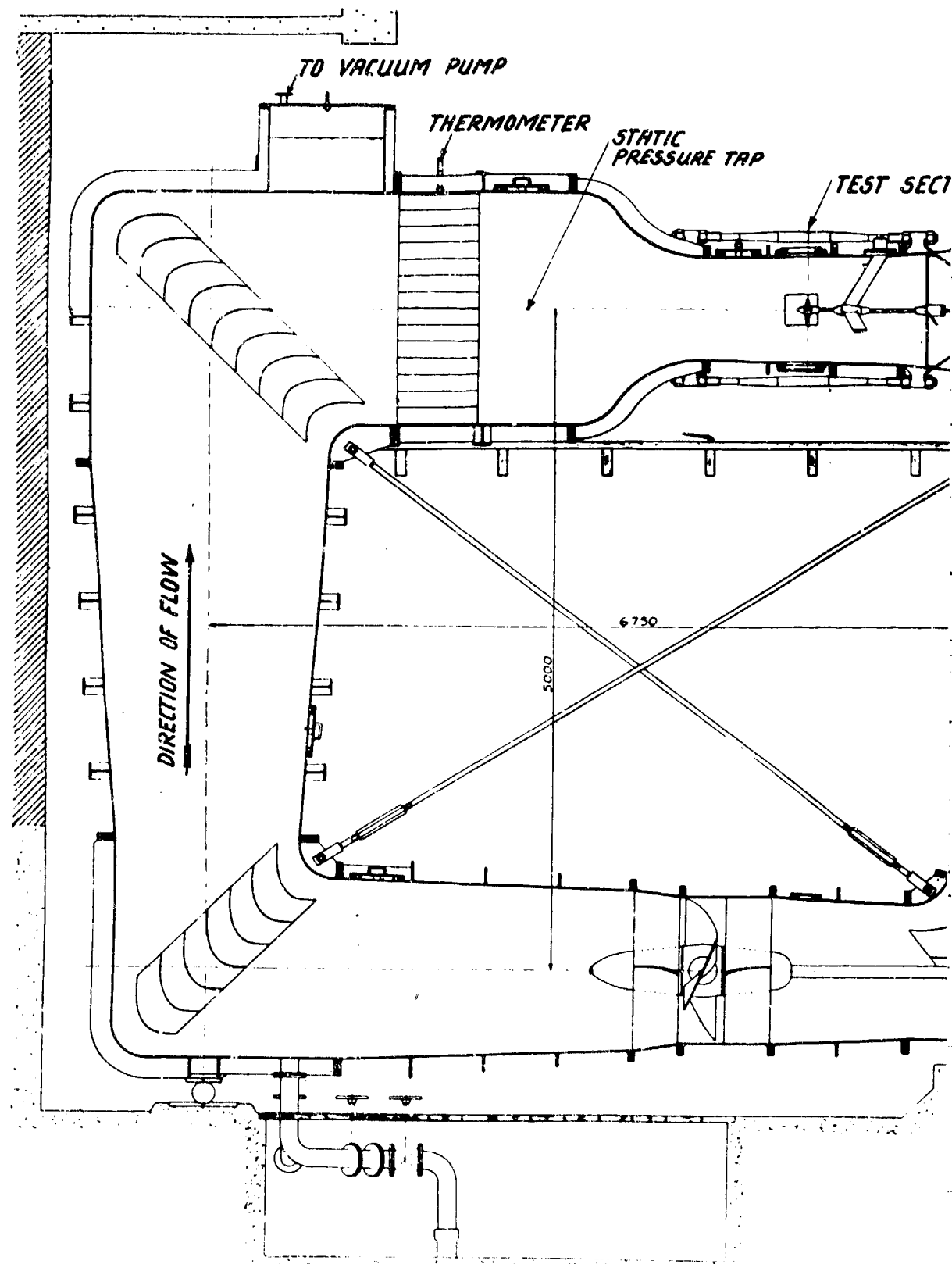
Propeller pump R.P.M. 380

Propeller dynamometer

Horsepower	40 at 2400 R.P.M.
R.P.M.	50 to 3500, ahead and reverse

Vacuum pump

Horsepower	3
R.P.M.	1100 to 2200.



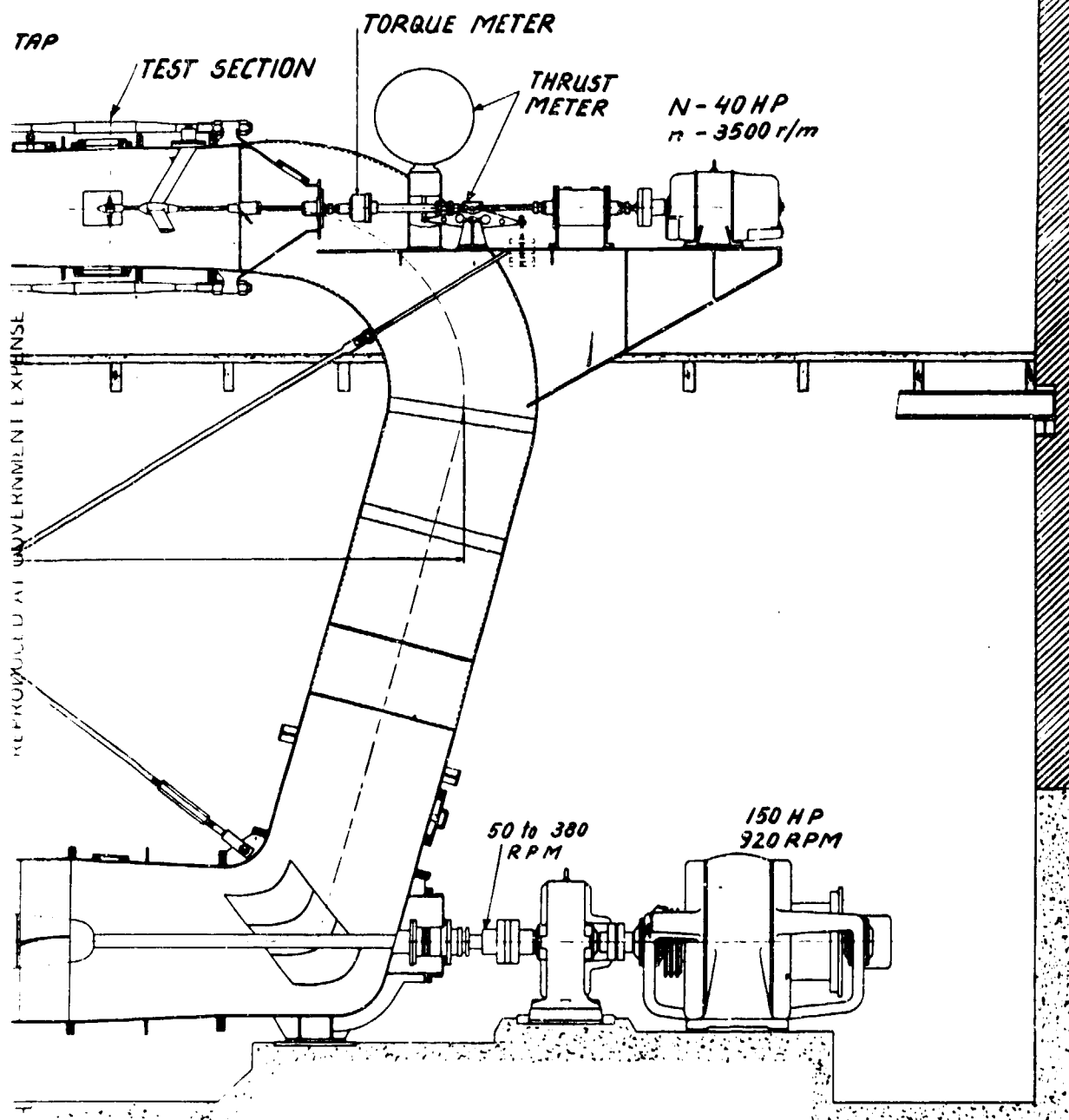


FIGURE: 68
CAVITATION TUNNEL OF
KARLSTADS MEKANISKA WERKSTAD
KRISTINEHAMN, SWEDEN.
DESIGNED BY H.S.V.A

RESTRICTED.

Cavittion Tunnels Designed by H.S.V.A. for Russia,
Japan and Sweden. Cont'd.

Since the Karlstad tunnel represents the most recent design of cavitation tunnels in Europe, certain trends in tunnel design are revealed by comparison with previous installations. The conventional H.S.V.A. rectangular cross sections, except in way of the pump, and the well-rounded divided elbow downstream from the test section are retained in the Swedish tunnel. However, the three remaining corners have relatively sharp bends of small radius with short guide vane grids instead of the previous larger radius bends with fewer, long guide vanes. Both at H.S.V.A. and Wageningen, opinion now favors sharper bends with short guide vanes at all corners except immediately after the test section, where danger of cavitation has led to the use of a well-rounded elbow.

The torque measuring arrangement of the Karlstads tunnel consists of the usual H.S.V.A. double shaft arrangement using a calibrated torsion rod, whose twist is transmitted by a potentiometer to a cross-spool instrument. For the thrust measurement, the conventional balance arm and dial scale is used, but the compensating chamber for eliminating the thrust correction due to the differential pressure on the shaft has been omitted. Evidently the convenience of eliminating the thrust correction has not justified the complications of an additional vacuum pump and a complex automatic pressure-equalizing device.

The water speed in the test section of the Swedish tunnel is measured either by means of a pitot tube or by the venturi method, using static pressure taps before the nozzle and in the test section. With the normal testing velocity of 5.5 m/sec., the variation of velocity over the whole test section is not greater than 1% (10).

For viewing the model, a stroboscopic lamp, actuated by means of contacts on the propeller shaft, is used. A very high capacity stroboscope has been ordered by the Karlstads firm for taking photographs with an exposure time of 0.002 seconds.

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VIII. Proposed Cavitation Tunnel III at H.S.V.A.

A. Design Considerations.

In order to be able to measure the lift and resistance of hydrofoils with and without cavitation for the purpose of obtaining basic propeller design data, a study of the design considerations for a suitable tunnel installation was made by Dr. Lerbs at H.S.V.A. in late 1941. Because of lack of materials and war difficulties, the construction was never begun.

Certain conditions were desired to be fulfilled in the tunnel design in order for the test profiles to represent propeller blades:

1. The lowest obtainable cavitation number should be the same or less than the lowest local cavitation number encountered with propeller blades,
2. The dimensions of the test section should be large enough to investigate the profile with the actual stagger and gap of the propeller blades.
3. The test section should simulate all the conditions prevailing inside the flow through the propeller disc so as to give a pressure rise to the blade row in the flow direction.

In determining the lower limiting cavitation number for the tunnel design, the local cavitation number for a blade tip in the vertical position was calculated for the German destroyer Z-36 and a VS-1 type motor torpedo boat. When neglecting the induced velocity, the local cavitation number,

$$\sigma_L = \frac{p_B + \rho h_t - p_v}{\rho / 2 \left[v_a^2 + (\pi n d)^2 \right]}$$

where p_B = barometric pressure

ρ = density of the water

p_v = vapor pressure

RESTRICTED.

Proposed Cavitation Tunnel III at H.S.V.A., Cont'd.

ρ = mass density of the water

h_t = depth of a vertical blade tip below the surface

v_a = speed of advance

n = revolutions per second

d = propeller diameter

Since the values of σ_L for Z-36 and VS-1 were .035 and .036 respectively, Lerbs considered that the tunnel design should aim for a cavitation number of 0.01 to 0.02.

In order to get an idea of the value of the cascade stagger and gap (Fig. 69) Lerbs plotted the stagger ratio, s/l , and the gap ratio g/l of the Schaffran B series against the radius ratio, $x = r/R$, where

$$g = \text{cascade gap} = \frac{2\pi r}{z}$$

l = blade width

$$s = \text{stagger} = g \cos \beta$$

r = radius of any point

R = radius of blade tip

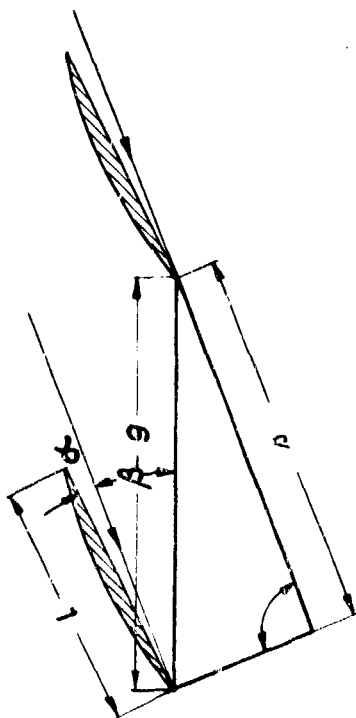
$$\beta = \text{hydrodynamic pitch angle} = \tan^{-1} \left(\frac{p}{2\pi r} \right) - \alpha$$

p = pitch

α = angle of attack

z = number of blades

Taking $x = \frac{r}{R} = 0.7$ and developed area ratio = 0.6 for the fundamental design, the stagger ratio s/l and the gap ratio g/l are approximately 1.5. Both ratios decrease with an in-



$$1.) g = \frac{2\pi r}{Z}$$

$$2.) A = g \cdot \cos \beta$$

$$\beta = \tan^{-1} \frac{p}{2\pi r} - \alpha$$

FIGURE: 69

RESTRICTED.

Proposed Cavitation Tunnel III at H.S.V.A. Cont'd.

crease of the developed area ratio. Lerbs assumed that two additional profiles on each side of the tested profile are sufficient for obtaining the correct data for the influence of the cascade. Since the length of the test section depends on the stagger ratio and the number of profiles, the minimum test length for 5 blades amounts to 7λ for $s/\lambda = 1.5$.

The height and width of the test section depends on whether the blade row is expanded in a vertical or a horizontal direction. Since the cavitation number is constant only in a horizontal level, the number will vary from profile to profile for a vertical arrangement; with a horizontal arrangement all profiles are equivalent, but the cavitation numbers vary along the blade width. Also the height of the test section is limited by the necessity for avoiding cavitation in the top of the test section. Assuming $g = 1.5\lambda$ and allowing 1.5λ clearance at the top and bottom on the vertical arrangement, Lerbs arrived at a test section height of 9λ for 5 profiles⁹. A hydrofoil width of 0.1 meters (3.94 in.) was determined to be satisfactory for strength when assuming a profile fixed at both ends, with blade thickness fraction 0.02, $v = 20$ m/sec (38.9 knots) and the lift coefficient $= 1.0$. Therefore, the test section dimensions were set at 0.9 m (35.43 in.) in height and 0.1m (3.94 in.) in width.

The minimum testing length of $0.7\lambda = 0.7$ meters was not considered sufficient to obtain a uniform velocity distribution. Based on Nikuradse's velocity distribution measurements

⁹The vertical height 9λ was erroneously based on a vertical spacing between hydrofoils of $g = 1.5\lambda$. Actually the vertical spacing should have been $g \sin\beta = 1.5\lambda \sin\beta$ (see Fig. 69). The test section height would be only 6 to 7λ , with a resulting smaller tunnel and less danger of cavitation in the test section due to the variation of the hydrostatic pressure. This error was recently pointed out to Dr. Lerbs, who confirmed the mistake in the proposed design.

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Proposed Cavitation Tunnel III at H.S.V.A. Cont'd.

in pipe lines with turbulent flow, a length of 2.5 meters is required to establish uniform flow. A test section length of about 3 meters was therefore proposed.

In order to obtain a pressure rise in the direction of flow, the walls would have to be made divergent. For fast ships screws in which the pressure rise is slow, it was questionable whether a pressure rise in the flow direction was necessary for the cascade tests. In the proposed tunnel, Lerbs used parallel walls with no pressure rise.

The maximum velocity for a minimum cavitation number of 0.015 was obtained by the formula $\frac{H}{2} = \frac{v^2}{2g}$ ✓

$$\text{or } v = \sqrt{Hg} = 24.2 \text{ m/sec (47.1 knots)}$$

where H = height of test section = 0.9m.

The flow capacity, $Q = A_c \cdot v = .1 \times .9 \times 24.2 = 2.2 \text{ m}^3/\text{sec}$,

where A_c = area of cross-section.

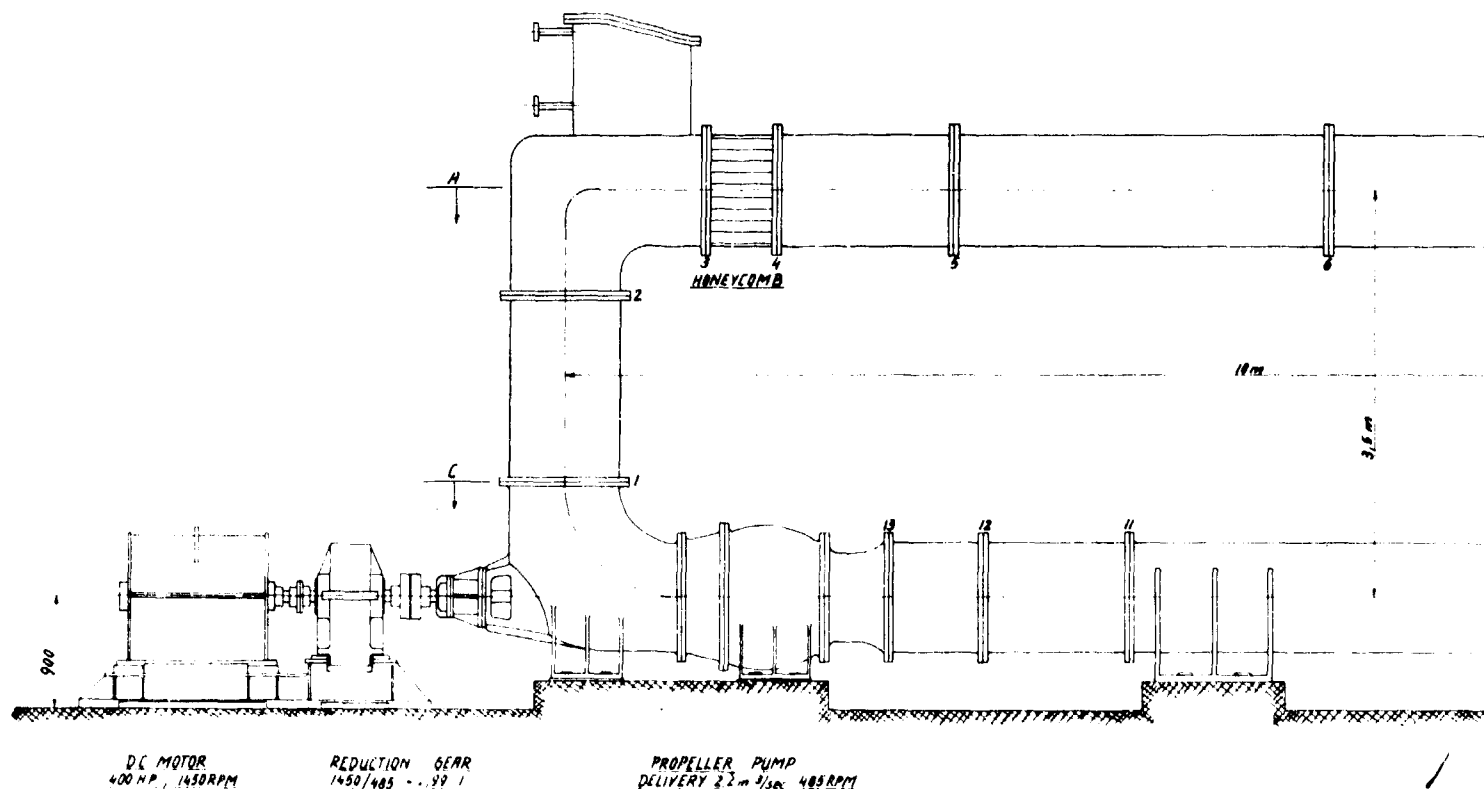
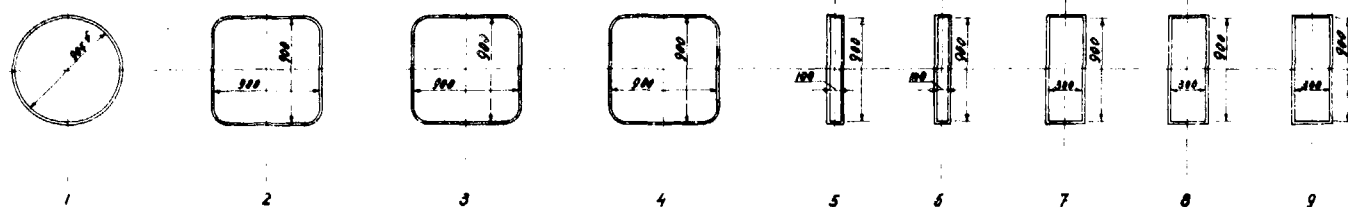
Therefore the motor H.P. = $\frac{3}{75} \cdot 1/2 \rho v^2 \cdot k$, where k equals

Motor power input. If $k = 0.4$, based on previous tunnel water horsepower designs, the required motor H.P. = 352. By adding a cascade loss of 24 H.P. resulting from a drag coefficient of 0.05, the total motor power became 376. A 400 H.P. unit was proposed. The final tunnel design is shown in Fig. 70.

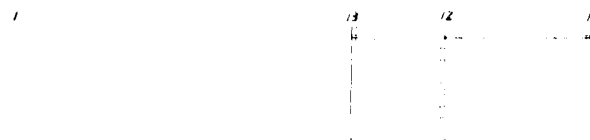
B. Measuring Instruments.

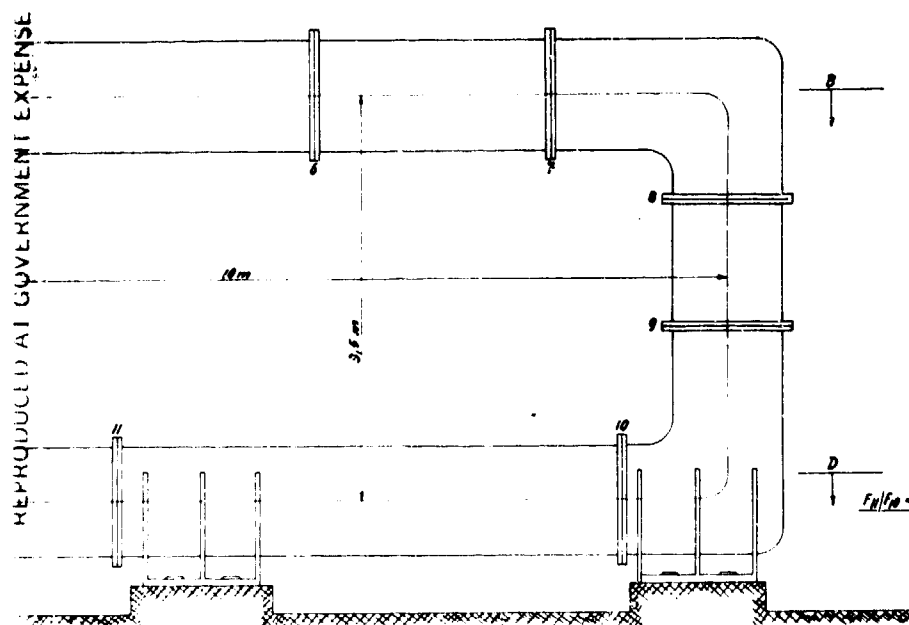
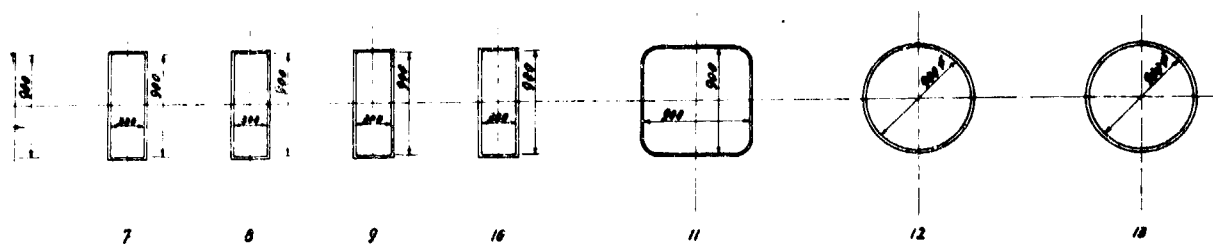
For measuring lift, drag and moment, a three-component dynamometer was to be designed. The resultant force was to be separated into vertical and horizontal components by two frames, and the vertical component was to be further subdivided into forward and after lift components. The intended method of measuring all of the component forces was by means of running-weight balances, according to the system used in the D.V.L. wind tunnels in Berlin (11). In this system, a small

NOT TO SCALE AT GOVERNMENT EXPENSE



ARRANGEMENT OF THE CORNER GUIDE VANES





VELOCITY IN THE TEST SECTION (5-6) = $24 \text{ m/sec} = 44.7 \text{ Knots}$



WATER VOLUME $\approx 12 \text{ m}^3$
PLATE THICKNESS 12 mm

FIGURE 70
DESIGN OF A CAVITATION TUNNEL
FOR HYDROFOIL RESEARCH
AT H.S.V.A

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Proposed Cavitation Tunnel III at H.S.V.A. Cont'd.

motor, actuated by contacts on the balance arm, moves the balance weight on a screw to maintain automatic balance. No measuring rods with stuffing boxes would be required, for the measuring parts could work in the water in an air-tight casing on the side of the test section. Only static stuffing boxes for wiring to the recording instruments would be necessary. For regulating the contacts in the water, a selenium photoelectric cell was intended to be used outside the tunnel.

The angle of attack of the profile was to be measured from the horizontal centerline and was to be corrected for the bending of the flow lines induced by the horizontal boundaries of the test section.

The velocity in the test section was to be based on the pressure drop through the nozzle, taking account of the inserted hydrofoils and the cavitation space.

The static pressure at the tested profile was to be calculated from static pressure measurements taken sufficiently far ahead of the profile row. The temperature was to be taken by thermometers at the points of lowest flow velocity.

C. Auxiliary Installations.

With a given velocity, the cavitation number was to be controlled by regulating the pressure in the dome before the nozzle. With a 10 to 1 contraction between the dome section and the test section, a pressure above atmospheric is necessary in the dome section to obtain a cavitation number of 0.015 at velocities above 15 m/sec (29.2 knots). Therefore a special regulating device is required for controlling the pressure in the dome. The type of device had not been chosen.

Since with low cavitation numbers the static pressure approaches the vapor pressure, the temperature should be kept constant to maintain a constant cavitation number. Because of the large energy input of the proposed tunnel, a cooling

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